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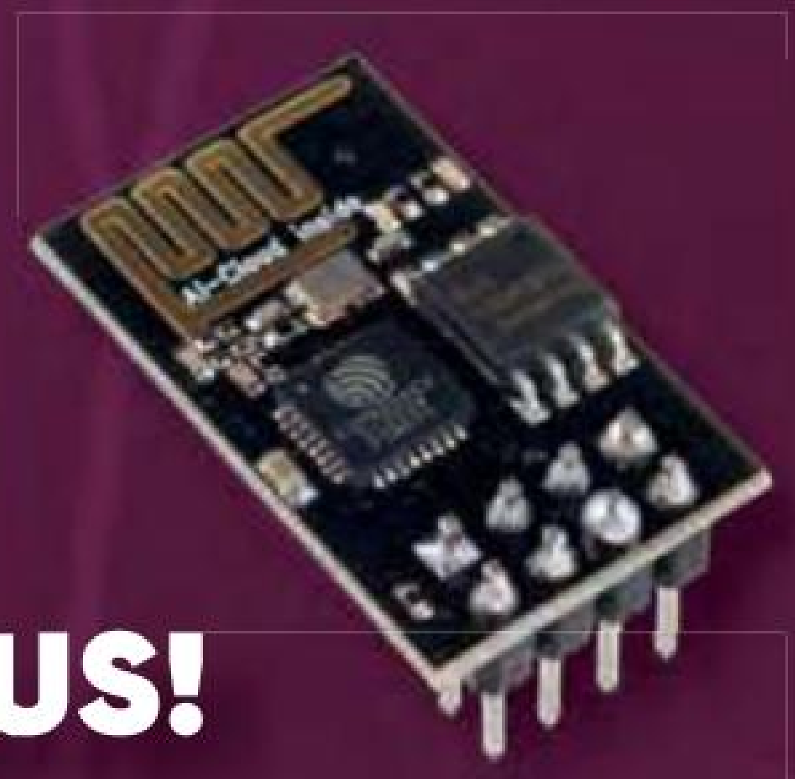

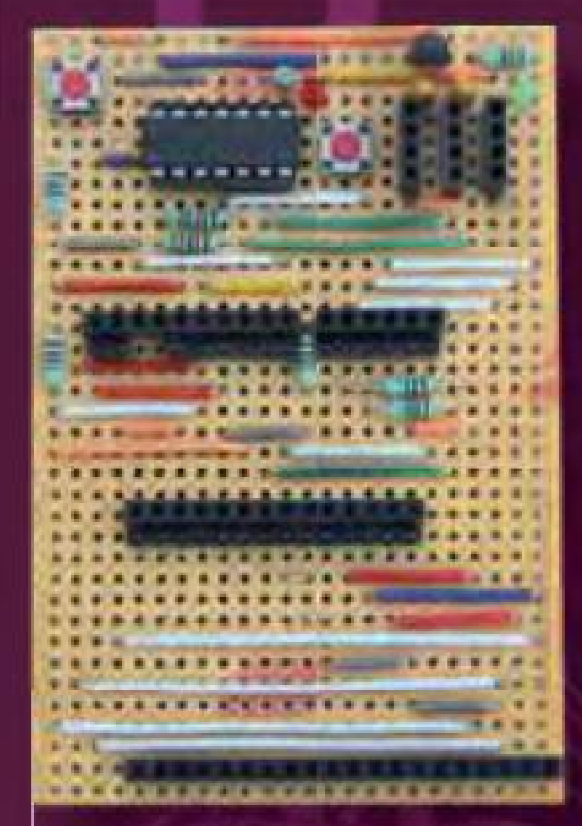

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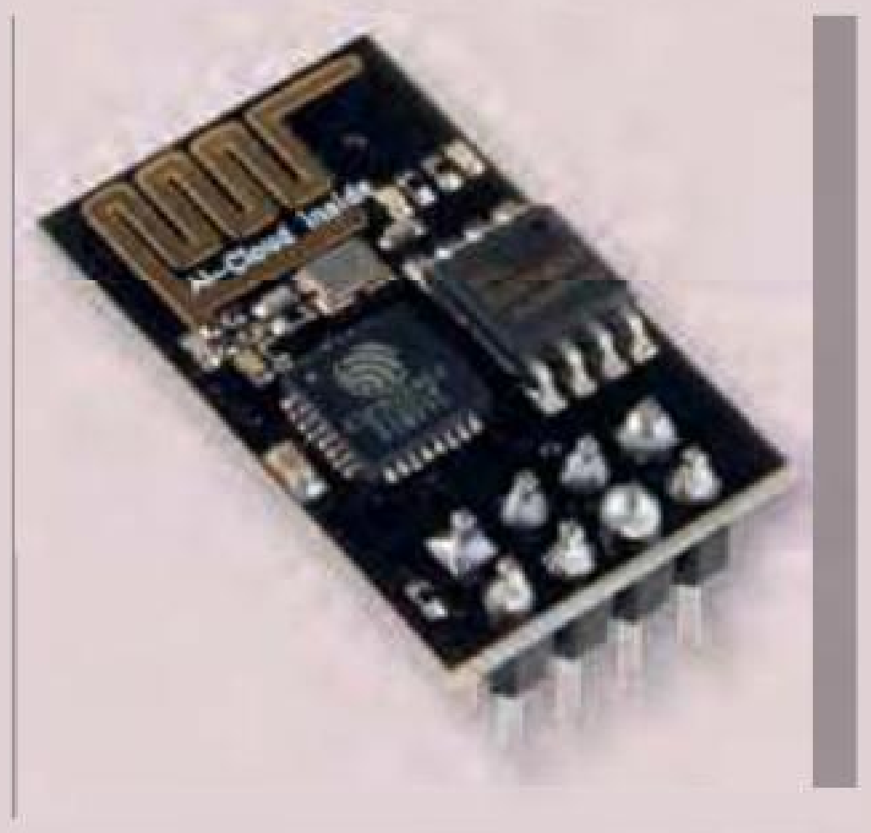

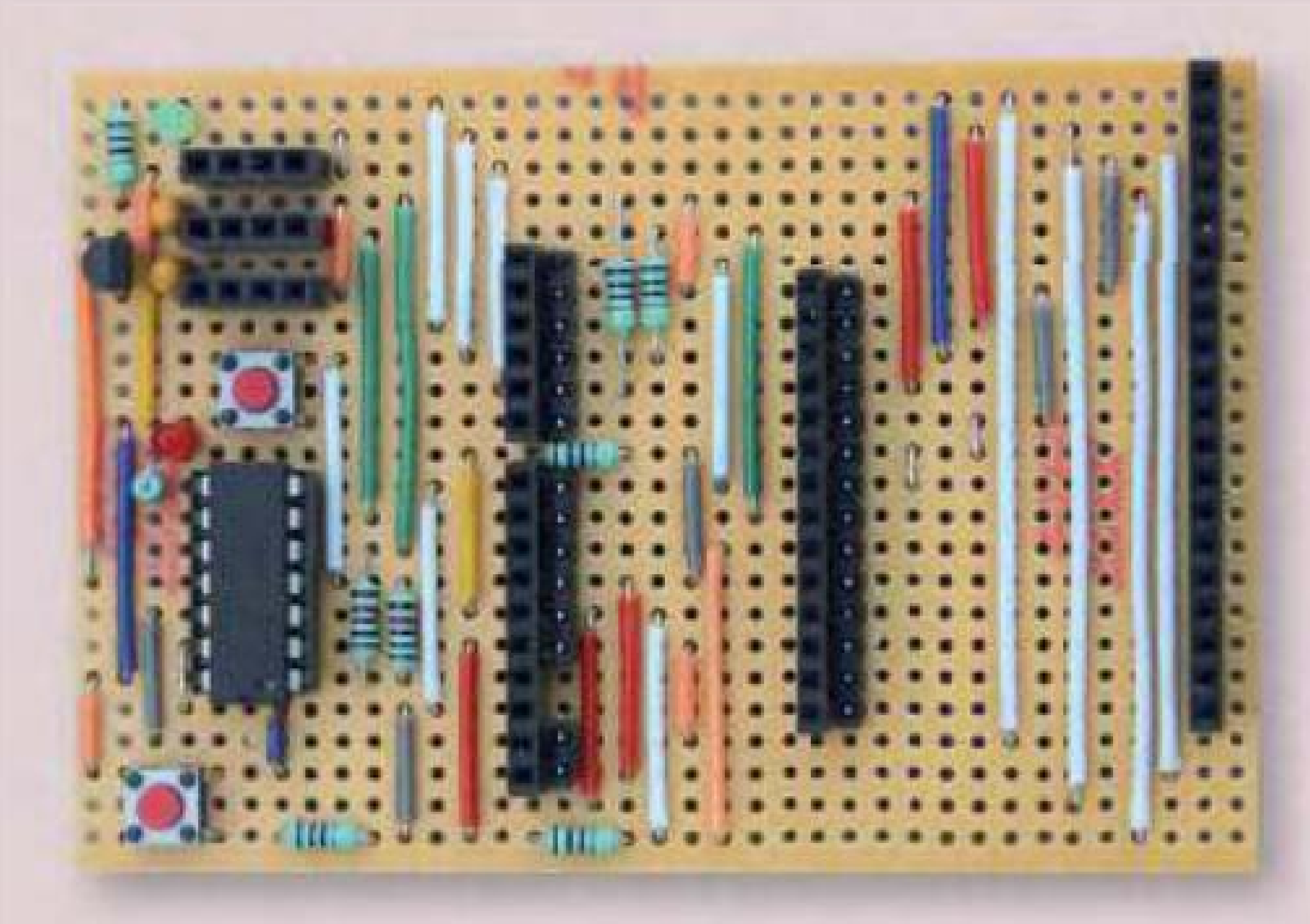

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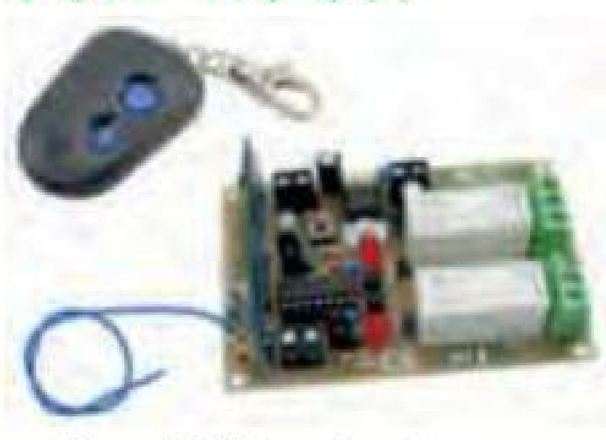

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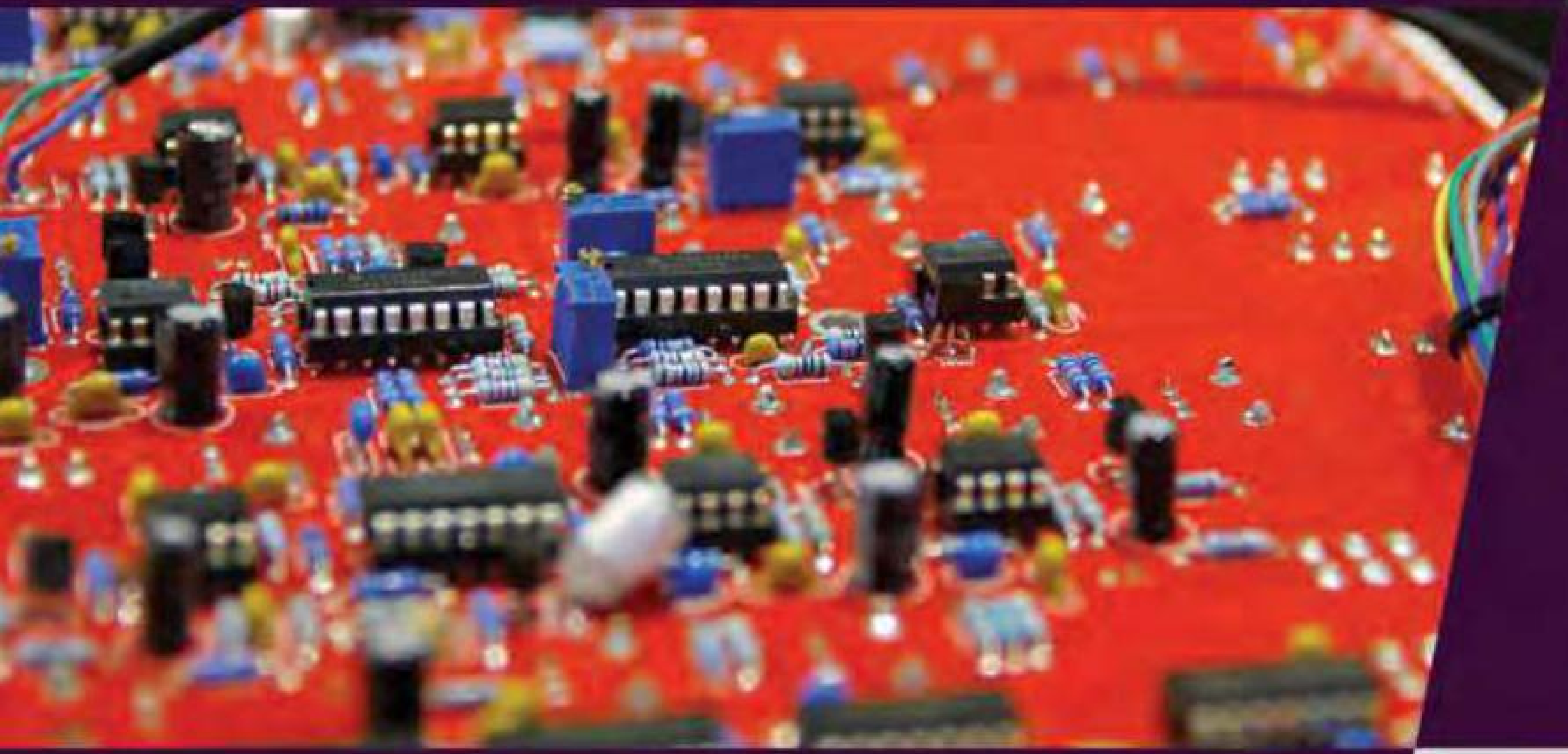

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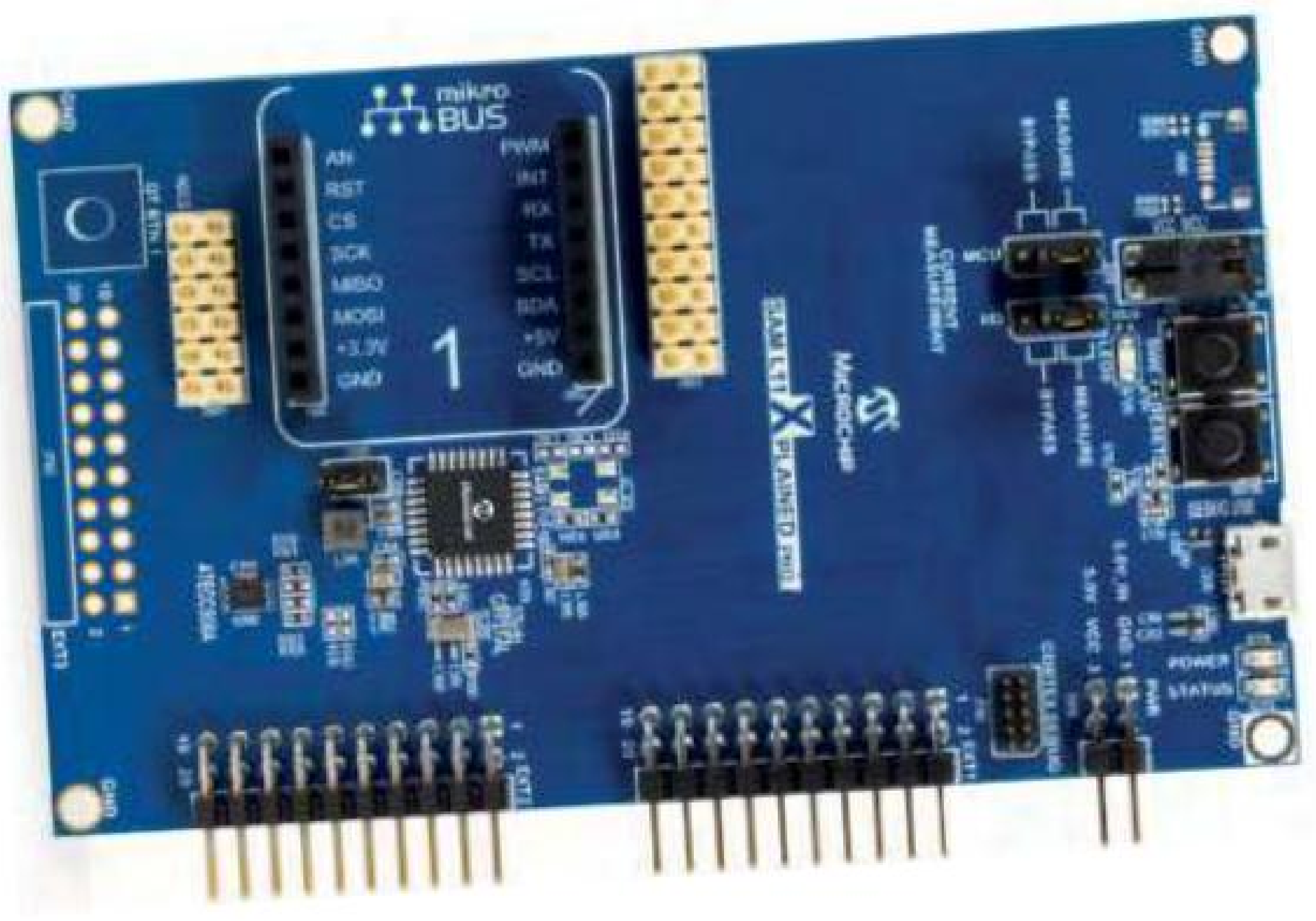

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Getting practical

Here, at last, we are 'back to the future' with our first issue of *Practical Electronics*. To be clear, this is Electron Publishing's first 'PE', not the very first issue with that name. In fact, this is a long-overdue reversion to the magazine's much-loved original title, which was launched back at the end of 1964. It was a great magazine then, and we are determined to continue that tradition of quality 55 years later.

The aim of *Practical Electronics* is simple – to provide you with the best available hobby and home construction projects, theory, articles, tips and advice to enable you to enjoy the exciting world of electronics. We will certainly continue with the best of *EPE*, but as regular readers will have noticed, as well as a redesign, we are introducing new material and new columns. Think of it as steady evolution rather than hasty revolution. For example, this summer, we will bring back the *Practically Speaking* column (especially appropriate for a magazine called *Practical Electronics*), which came to an end with the retirement of Robert Penfold in 2016.

We now move on to revamping the website and online shop, which will take a few months to get right, so for now please stick with the **www.epemag.com** for all your online needs. In the meantime, we will start a new aspect of the magazine's online presence via Instagram and Twitter, where you can see previews and snippets of upcoming items, plus anything else that we think readers might find interesting. You can find us at:

Instagram	**practicalelectronics**
Twitter	**@practicalelec**

We hope you enjoy this first issue of *PE*, and will join us on our journey to develop your magazine.

Matt Pulzer
Publisher

Follow-on festival

Techno Talk

Mark Nelson

Now and again it's worthwhile following up new developments concerning topics covered previously, and sharing interesting comments sent in by our loyal readers. So, without further ado, let's get cracking.

We start with new variants of junk phone calls. Our Kentish correspondent reports that these criminals are getting cleverer. Now it's: 'The breakdown cover on your Sky Box has expired, special renewal offers, just give us your card details'.

Corporate incompetence

He reports his conversation as follows. I knew it was a scam, so I played along to waste their time, saying I would renew for a year and that they should use my existing payment details. 'Oh no, we can't do that, data protection means we don't keep these details on file,' was the reply. I told the agent if they didn't have my bank details on file, they must be fraudsters. '**** you' was the response, before 'Sarah' hung up.

The scammer's number displayed on my phone – 020 3807 6171 – is a virtual number licensed by OFCOM to DIDWW Ireland Ltd, and should have been shut down. If you call the number, it goes through to a professionally recorded call centre message. Perhaps the fraudsters have spoofed a genuine Sky number to reassure anyone who has second thoughts, but it's more likely that the call is routed to the scammers who have recorded (or copied) a very convincing greeting message. Meanwhile, OFCOM and the ICO both remain asleep at the wheel. Note: the real number for Sky breakdown cover is 0800 561 4457.

Natural human curiosity

Roger from London tells us he had received four calls on his mobile over six days from +265 88 xxx xxx (which is a number in Malawi). It always rings once only and then hangs up before you have a chance to answer. This fraud exploits people's curiosity, who then call the number to see who was calling them. To call the number displayed will probably cost you an arm and a leg, especially if you spend time listening to a lengthy recorded announcement. This type of scam is called a 'Wangiri call', Japanese for 'cut and run'. Malawi is not the only apparent source of these calls, which can also purport to originate in Comoros, Liberia, Tunisia, Nauru, Mauritania, Chad or the Cook Islands.

In reality, the source number is almost certainly spoofed, the true location being in some other country. In fact, your reply to that number may be 'terminated short' at the international telephone exchange in London and diverted to a premium rate number here in Britain, never leaving the UK. There was a major scandal of this kind a while back, in which calls to the tiny country of Tuvalu were answered in Manchester. For further information I recommend two Wikipedia articles, **bit.ly/pe-apr19-01** and **bit.ly/pe-apr19-02**, and also **bit.ly/pe-apr19-03**, which explains the baffling way these calls are redirected through multiple mobile networks where the caller ID number can be altered.

Cheap stamps

In the January 2017 issue, I explained how Chinese traders selling on eBay and **AliExpress.com** could afford to sell so cheaply. However, I failed to explain the full story; not only are the goods cheap, postal costs are also cut-price. Britain's Royal Mail has what it calls a strategic arrangement with Alibaba, the owner of the consumer marketplace **AliExpress.com**. Royal Mail provides these Chinese exporters with a special deal that enables them to supply goods for UK delivery within two weeks, much faster than standard international postage from China.

Another, often unrecognised factor, is that China enjoys subsidised postal rates for items sent to Europe, the US and many other countries. This is because the UN (United Nations) still classifies China as a developing country, despite the enormous strength of its economy, which enables Chinese companies to flood Western markets with products that are often cheaper than those produced locally. Cheaper postage is coordinated via the UPU (Universal Postal Union, an agency of the UN). The UPU organises the worldwide postal system and allows developing nations to pay lower rates than the wealthiest nations for having their mail delivered abroad.

Trump stamps his authority on the UPU

The well-known contrarian Donald Trump argues that the subsidised rates enjoyed by China cost the US about $300m per year. Last October, the US formally moved to withdraw from the UPU, so that it could establish its own prices for delivering international packages. The consequence of this move would force Chinese sellers to pay higher postal costs, bringing to an end the bizarre current situation in which it is cheaper to send most parcels from China to the US than to post them domestically within the US. However, as commentators observe, Trump has characteristically overlooked the negative consequences of his threatened move. Negotiating postal treaties with individual countries would be time-consuming and expensive, as well as raising prices for US consumers. And by pulling out of the UPU instead of working to reform it, the US would forego a key opportunity to pressure China to reform, with the support and backing of allies; it also hands China greater influence in the UPU.

And finally

Tolerance is a virtue – but it comes at a price. Where resistors are concerned, tolerance refers to the percentage of error in its resistance, or how much more or less you can expect a resistor's actual measured resistance to be from its stated resistance. For the projects we build, 5% tolerance (gold band) or 10% (silver band) are normally, well, tolerable. But what does a resistor manufacturer do when a client asks it to supply relatively small numbers of a non-standard value? The former Synchronome clock company required spark quench resistors of exactly 37Ω (no more, no less). According to Andy Young on the Electric Clocks forum, suppliers took items from stocks of the closest standard value having plus or minus 5% accuracy, selected those of the exact desired value, stripped off the existing painted markings and repainted new ones.

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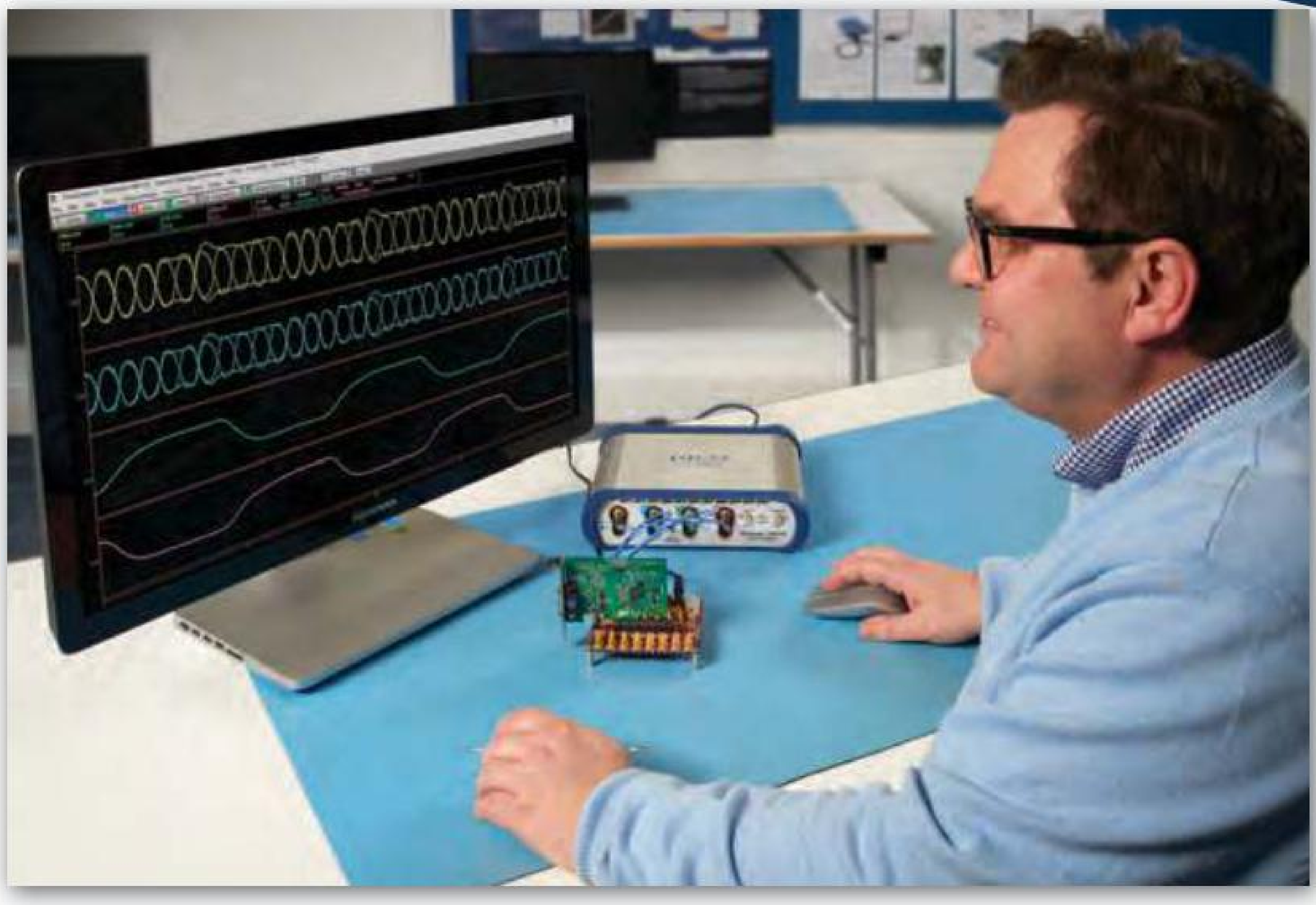

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Ordering information

Order code	Model number	Description	USD*	EUR*	GBP*
PQ181	PicoScope 9404-05	5 GHz 4-channel oscilloscope	14,105	11,975	9,900
PQ067	PicoConnect 910 Kit	Six microwave and pulse probe heads with two cables	3,095	2,595	2,045

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Net Work

Alan Winstanley

Alan Winstanley reminds readers to keep a variety of back-ups in the never-ending drive to go digital, makes up his mind when it comes to smart speakers, and 'likes' a Dubliner for taking a stand!

Welcome to this month's *Net Work*, our monthly round-up of trends and developments for Internet users. In the last month or two I've described the moves towards 'going paperless' with ever more communications being handled via web-based systems. This raises the question of how, in a paper-free society we should save important information for the future. Taking a last-gasp, virus-free backup of important folders onto a portable USB hard disk might be worth thinking about, especially to insure against threats from ransomware. The author backs up a RAID NAS array on a 2TB drive several times a year, which is a slow and onerous job, but a valuable insurance policy too.

Back to the future

Another question is that of backwards compatibility – will you be able to read key data files in the future? An example arose recently when compiling a claim for a Payment Protection Insurance (PPI) policy refund. Readers in the UK will know that Britain's Financial Conduct Authority has set a deadline of 29 August 2019 for claims about mis-sold policies to be submitted, so in my dusty old archives I found some floppy disks – Microsoft Money 1.0, no less, and a data backup from nearly 20 years ago. Would those floppies still read properly? Luckily, indeed they would, and within ten minutes a legacy version of MS Money was running on an old W98 machine and the data file was imported. Then I printed a report listing all PPI premiums that had been paid over many years. After doing the same with Quicken-based accounts, claims were submitted via the user-friendly Resolver website (**bit.ly/pe-apr04**). This admittedly extreme but satisfying example shows there is something to be said for not only archiving data files safely, but also retaining compatible software and the hardware to run it: you just never know if you will need it again.

Britain's HMRC (Her Majesty's Revenue and Customs) and National Health Service (NHS) are also doggedly going digital. HMRC's drive for 'MTD' (Making Tax Digital) is 'encouraging' (bulldozing) all taxpayers into 'doing it online', while NHS England is finally banning fax machines – a vintage back-up technology that I witnessed in use when a computer virus took down a hospital's IT networks a year or two ago.

Another NHS proposal designed to ease pressure on services suggests that patients could have a doctor's consultation over the web, by Skype. Naturally, some are disturbed by the loss of personal contact and the inaccessibility of Skype to some patients. The idea could be likened to Australia's School of the Air, a two-way radio service that used the Flying Doctor wireless network to educate children in remote areas (explained at: **bit.ly/pe-apr05**). The invaluable 50-year old service is being modernised using Internet-based services instead. We will all have to embrace changes that the Internet is bringing, and the unstoppable trend towards paperless and impersonal communications marches onwards.

Google vs Alexa showdown

Smart speakers such as Amazon's Echo and Google's Home Mini are becoming popular, and for several years the writer has agonised over which system to choose (if any at all), mainly because of privacy fears and the feeling that the gadgets are always 'listening in'. I recently quizzed my Echo Dot about whether a particular store in town would be open on a Sunday. Alexa triumphantly assured me that it was, until 4pm, so I headed off in the car only to find the store shutters were firmly down and my 20-mile journey had been wasted. Back home again I posed the same question to Google Assistant, which declared: 'No! It's closed on Sundays!'

It's unfair to compare devices directly this way because Amazon was never likely to improve upon Google Search nor the local business data that Google has curated over many years. There is no doubt that Google is becoming ever more refined at a granular level and eventually my mind was made up thanks to a seasonal price cut. A trio of Google Home Minis soon arrived and one of them now jostles for attention alongside a forlorn Amazon Echo Dot.

They are subscription free, but a Google account is needed along with the Home app for Android or iOS. After a few weeks I've come to appreciate how incredibly useful a Google Home Mini can be, and its voice recognition and the sensitivity of its two far-field microphones are second to none. I must admit to side-lining any privacy fears and giving these devices the benefit of the doubt, but in my view its many benefits now far outweigh the need to prefix everything with, 'Hey Google'. The Home Mini also integrates perfectly with a Google Chromecast TV media player, and overall the system hangs together very well. They are 5V USB powered, but for cordless operation, rechargeable battery bases for both systems are made by Ninety7 (**https://ninety7.com**) available – of course, if a little ironically – through Amazon (also Argos and similar).

Thunderbirds' 'Brains' invents a robot. Any resemblance of the author to either of them is entirely coincidental, see: https://youtu.be/V0YQ6Q_AQZc

Even as a spell checker or talking dictionary, alarm reminder, speaking clock, simple PA system (eg announcing dinner's ready) or for operating smart devices, it is becoming abundantly clear that always-on, voice-driven smart devices like these are finding favour in many homes and on many desktops too. *PE* readers will probably prefer the Google device for general use, while Echo is more family and shopping orientated.

Century 21 Television

As a child of the 1960s, your spellbound scribe looked forward to Sunday afternoon television, especially the futuristic *Thunderbirds* series created by Gerry Anderson's Century 21 organisation, which would inspire the writer to build proper little electronic control panels and gadgetry for *Everyday Electronics* a decade later. Schoolteachers dubbed television 'the Devil's Lantern', and life and family viewing (with the emphasis on 'family') involved spending quality time watching live scheduled broadcasts from just three channels of public service broadcasting (PSB) and commercial TV.

Fast forward 50 years to the end of 2018, and Britain's communications regulator (Ofcom) conducted research into the viewing habits of children today. The study focused on the so-called 'screen time' that they spend viewing streaming video on 21st-century appliances such as tablets and PCs. Ofcom's January 2019 report, *Life on the small screen: what children are watching and why* (**bit.ly/pe-apr06**) confirmed what many of us suspected and feared: youngsters' interest in scheduled programmes on PSB had all but disappeared in favour of watching Netflix and YouTube online instead. These were named as the top two go-to destinations for kids searching for streaming content, a trend that is widely accepted to be a permanent structural change, says Ofcom. Furthermore, the brand awareness of these streaming packages among children was much higher than, say, that of the BBC.

Also highlighted was the startling evidence that today's children preferred watching Netflix and YouTube alone in their rooms, and the 20th-century aspiration of spending 'family time' watching TV together – often tuned into a programme not of a child's choosing – was anathema to them. Ofcom found that kids enjoyed watching what they want, when they want, and they also had an extremely strong preference for keeping in touch with their friends via social networking and video gaming rather than in person. No 'self-driven' hobbies, clubs, bike rides or get-togethers with school pals for them, though they did often watch YouTube to glean ideas connected with their interests or pastimes. Many parents tried hard to break their childrens' online addiction but, sadly, out-of-school face-to-face activities were deemed to be too much bother for this unmotivated Netflix generation.

According to Ofcom, children clearly enjoy searching Netflix to find content that they could consume immediately. They may watch replays of TV shows like *Strictly Come Dancing* or *X Factor*, not realising that they originated from PSB television; in fact many did not even understand what a traditional TV 'channel' was (nor a YouTube channel either, for that matter). A very common trait was the instant and effortless gratification experienced by young YouTubers and Netflix users who also saw huge rewards from receiving streaming video 'Recommendations' that popped up based on their profile and viewing history. Admittedly, the writer can't criticise that as he enjoys using the same features when searching YouTube for music tracks.

Vlog on

The influence of vloggers (video bloggers) seen as role models by young viewers was in evidence, as impressionable minds could easily be swayed by recommendations seen on social media. Coincidentally, the UK Government's Competition and Markets Authority (CMA) recently had to secure an undertaking from 16 'celebrities' and self-styled 'influencers' to state clearly when they were actually being *paid* to endorse products online, as non-discerning users might think that the stars were simply offering their followers some genuinely 'impartial' personal recommendations.

As an aside, some 'social-media influencers' have created some self-inflicted problems of their own. In one celebrated case, a vlogger failed to see how offering to 'plug' a product or service in return for a 'freebie' (in this case, a mention in a vblog in return for a free hotel stay) might actually backfire on them. In a vlogger's mind, such a 'business request' is considered normal and they have no issues with any perceived bias or lack of credibility that this 'business model' might engender. However, the doughty owner of Dublin's White Moose Cafe & Lodge would have none of it, quite rightly, and a row spilled online. Much of what is presently wrong with this distorted media channel was exemplified by another vlogger who, if nothing else, at least tried to offer a balanced view of the hotel's stance, see: **https://youtu.be/toKzUe5D7zs** (5 mins, contains 'language'), which may leave many *Net Work* readers feeling a bit exasperated! Putting aside any feelings of *Schadenfreude*, readers might enjoy a follow-up piece by life coach Gerald Pauschmann on YouTube at: **https://youtu.be/zlmarLZpsyQ** (13 mins, contains 'language').

Australia's School of the Air is replacing radio services with online versions. (Courtesy of NSW.gov.au)

In their survey, Ofcom observed that children whose online 'phone time' was strictly controlled were in a minority, as parents struggled to impose simple rules. Some kids had also figured out how to circumvent controls by logging into Netflix using their parents' credentials instead. Is all of this a bad thing? Australia's School of the Air shows the good that can come out of distant communications between earnest and motivated users. Today, there are real concerns about the way that unrestricted, unfiltered and unedited access to online material is skewing the values and perceptions of today's young generation, but Ofcom's report still offers some glimmers of hope. Not all youngsters surveyed were consumed by Netflix and YouTube, and some were clearly motivated enough by what they saw online (eg, watching car repairs on YouTube) to want to do that as a job when they grew up – just as I was inspired enough to discover electronics after watching *Thunderbirds* on TV!

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Internet-based 'GPS' Time Source

By Tim Blythman

We've produced a number of GPS-based clocks over the last few years, but they can be problematic if you can't get a GPS signal – deep inside a building, for example. But how about this for a clever alternative: program a cheap Wi-Fi module to act as a time reference, kept accuracy via the Internet! It pretends to be a GPS unit, so any GPS clock can use it!

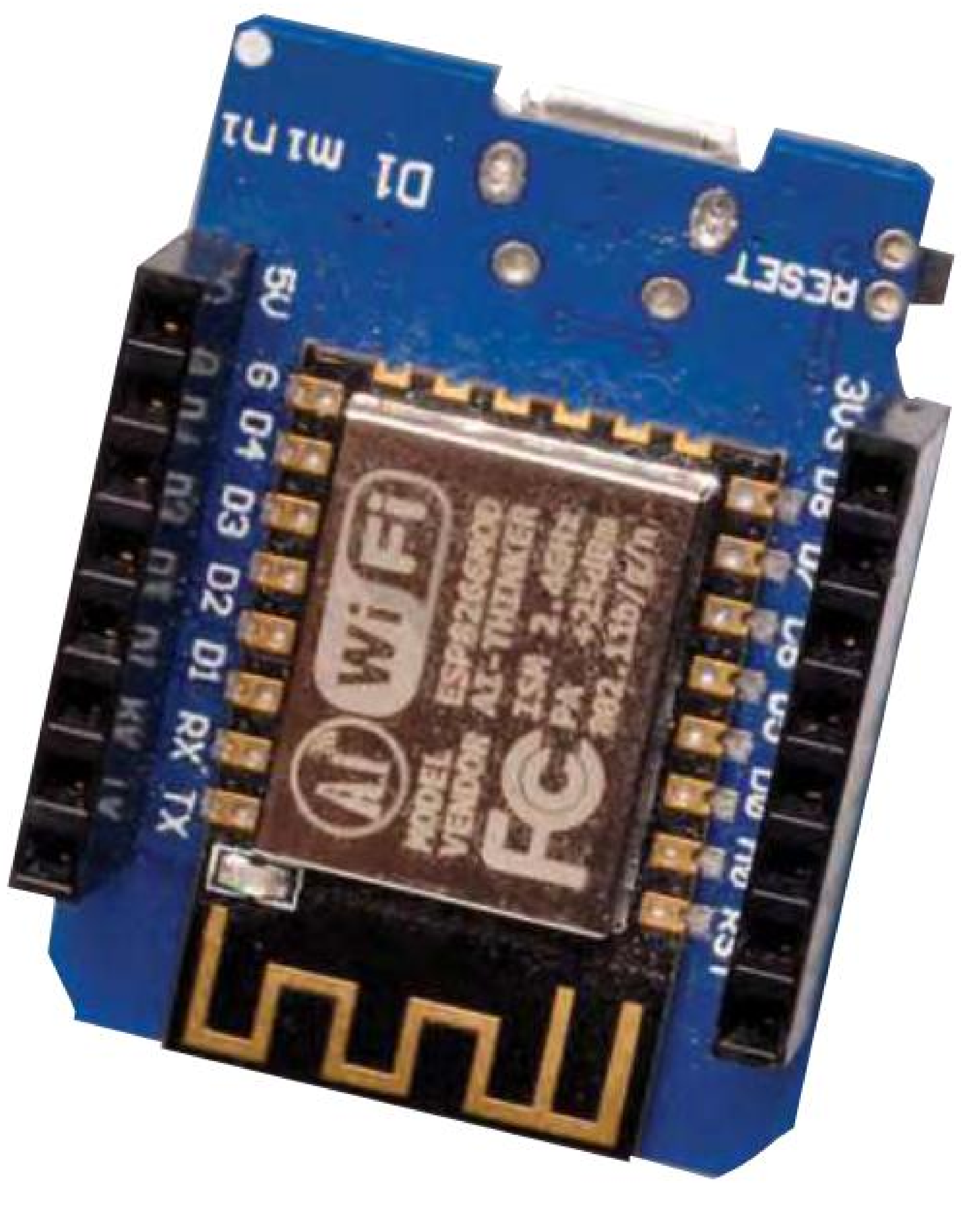
Clock projects that depend on a GPS source as the time reference can be relied on as being highly accurate – after all, the time code in the GPS signal is derived from an atomic clock.

The most recent GPS-synchronised clocks we've published are the *Analogue Clock Driver* (February 2018); and the *High Visibility 6-Digit LED GPS Clock* (January and February 2017).

In the case of the *High Visibility 6-Digit LED GPS Clock*, it requires no manual adjustments for daylight saving or time zones, as it can determine these adjustments based on location data from that same GPS module.

Unfortunately, all GPS-based clocks are subject to one caveat: they won't work well without having a clear 'view' of the sky, so that they can pick up the signals from multiple GPS satellites. While GPS signals can usually be picked up indoors, whether you will get them at a given location depends on the construction of the building, and even the weather.

But many readers will already have a Wi-Fi network at home and that gives an alternative source of time that's almost as accurate (far more accurate than you're ever likely to need!). So why not take advantage of it?



The NTP Wi-Fi module we chose, the ESP8266 WeMos D1 Mini Module.

This project takes a cheap and readily available ESP8266 Wi-Fi/ARM processor module and uses it to fetch accurate time readings from the Internet and pass it through to the clock.

The beauty of this system is that it presents this time reading as if it's coming from a GPS module, so you don't have to make any changes to the clock hardware or software. You could build any of our GPS clocks and with just a small amount of extra effort, get them to run off Network Time Protocol (NTP) time via your existing Wi-Fi network. It should even work with commercial, pre-built GPS clocks.

In fact, this concept can be used with any device that uses a GPS module to get a time signal. It doesn't need to be a clock. But keep in mind that it may not be accurate enough to use as part of a time reference system.

How it works

As already noted, we're using an ESP8266 module which is available pre-assembled, already having an onboard Wi-Fi transceiver. We program it using the Arduino IDE. IDE stands for Integrated Development Environment, which means that it lets you write code for an Arduino, then compile it and upload it to the board. And note this point; while we are using the Arduino IDE, we are not using an Arduino Uno or related Arduino board!

The software we have developed fetches the current time and date from an NTP server via the Internet, then it uses this timestamp in combination with its internal clock to generate a stream of GPS-compatible (NMEA encoded) data, including time signals.

It is possible to estimate your location based on your Internet IP address, so our software does just that, translating the IP into a latitude/longitude pair using an online service. So if you are using this module with the *High Visibility 6-Digit LED GPS Clock*, it can use these coordinates to calculate the correct time zone and daylight saving rules, and it will display the correct local time.

While we've found that the estimated position can sometimes be a few dozen kilometres out, in 99.99% of cases this will still be in the same time zone, so the time displayed will still be correct.

However, if you are using a proxy or VPN, this information may be inaccurate, as the IP service may return coordinates based on your proxy location. For most home Wi-Fi set-ups, this should not be a problem.

NMEA GPS data

NMEA stands for 'National Marine Electronics Association'; and NMEA 0183 is a specification for communication between marine electronics systems, including GPS receivers. Pretty much all GPS receivers produce serial data in this format, which is why we've designed our unit to use this same standard.

We've described the NMEA 0183 standard in detail in the past and we will give some examples below. But for now, you just need to understand that the data is sent over an RS-232 (or similar) serial link, in ASCII text format, with each distinct line being considered a 'sentence'.

Each of the 'sentences' is prefixed with a code, which indicates what data is contained within. So units receiving this data can skip any sentences with codes that they don't understand. Each sentence contains a series of values separated by commas and terminated with a checksum, so that data which is corrupted during transmission can be ignored.

Since the information from a GPS receiver is simply serial ASCII data, it's easy for a microcontroller to mimic it. A GPS receiver will usually transmit around 3-10 sentences, sent once per second. But for our clock projects, only two are important.

These are the RMC (minimum recommended GPS) and GSA (fix validity and active satellites) sentences. RMC contains the GMT/UTC time, date, latitude, longitude, speed, course and magnetic variation data. GSA indicates whether the unit has obtained a GPS fix and a partial list of the satellite IDs used to obtain that fix. See Fig.1 for an example. This was taken from a real GPS receiver.

Without an actual GPS receiver, the latitude, longitude and satellite status will have to be fabricated or estimated; the only information which absolutely needs to be correct is the time and date.

We've also written the software to produce a 'dummy' status sentence to show some information about the status of the Wi-Fi connection. Since this is a sentence type that the clocks are not programmed to interpret, they will ignore it. But you could monitor the output of the serial port using a PC as a debugging aid.

Network Time Protocol

NTP is one of the oldest Internet protocols still in use. It's used by pretty much every computer and smartphone to keep their clocks accurate.

NTP was designed to be simple and fast so that the overhead of checking and adjusting the time is minimised. It is well suited to implementation on a small device like an ESP8266 module. It's also designed to compensate for network delays.

Ultimately, NTP time comes from a source which typically has a caesium atomic clock. From there, the time is distributed to other nearby servers. Our unit will most likely be getting its data via a path that is three or more levels (or 'strata') removed from the atomic clock.

In other words, we're synchronising our time to servers, which synchronise their time to other servers, which synchronise their time to other servers, which have atomic clocks attached. Whew!

But you can still expect the resulting time to be accurate to within about 10ms. Given that we are transmitting this data to a clock which will be only be displaying to the nearest second, that should be accurate enough.

To determine the time using NTP, the unit sends out a number of packets over the Internet to NTP servers and uses its internal clock to keep track of when each packet is sent and when a reply is received. The response also includes the time (according to the server) when our query was received and when the response was sent. The packets are sent using the low-overhead User Datagram Protocol (UDP).

Using this information, we can determine the round-trip time; ie, the time it takes for our query to get to the server, plus the time it takes to get the response. Normally, the route taken by both packets will be similar and so the delay will be similar.

By subtracting the time that the server spent processing our request from the round trip time and dividing by two, we can get a pretty good idea of how long the response took to get to us. We can then add that delay time to the accurate time we receive from the server and that should be close to the exact time when the response was received.

Since we query a number of servers, if a majority of the times determined from the responses are within a few milliseconds of each other, then we can be fairly sure that we have a good determination of the time and we can average those results and use that as the correct time.

Keeping track of time

The NTP-based *GPS Time Source* uses its internal oscillator and timer to keep track of time in the short-term, so it does not need to constantly re-query the servers to determine the time.

This oscillator's frequency may not be exactly right and it could vary with temperature and other factors, but since we synchronise it frequently using NTP, it should never drift very far.

In fact, by looking at how it's drifting each time we get a time update via NTP, we can account for and cancel out some of this drift.

That's important, since we use this oscillator to determine the one-second intervals on which to send the NMEA data and this gives the clock its seconds 'tick'. If that was inconsistent or worse, glitched (eg, giving two pulses in short order), you would probably notice.

By default, we perform an NTP update at hourly intervals. The oscillator in the ESP8266 micro is typically accurate to within about ±0.001%. That means that, uncorrected, it will drift by up to 42ms each hour. That's hardly noticeable and the corrected drift is likely to be well within 10ms. You aren't going to notice a 10ms 'jump' when the time is updated from NTP.

One thing we haven't mentioned yet is that there are actually two different hardware units which you can use for this project. One is smaller and cheaper (ESP-01) but only has eight pins. The slightly larger module (D1 Mini) has more pins and this allows us to also provide a 1PPS (one pulse per second) output, for clocks which require it. See Figs.2, 3 and 4 for details of the D1 Mini.

If available, the 1PPS output is generated from the same oscillator and is driven high briefly at the same time that we start to transmit the NMEA data. We'll get back to discussing the two different hardware modules later.

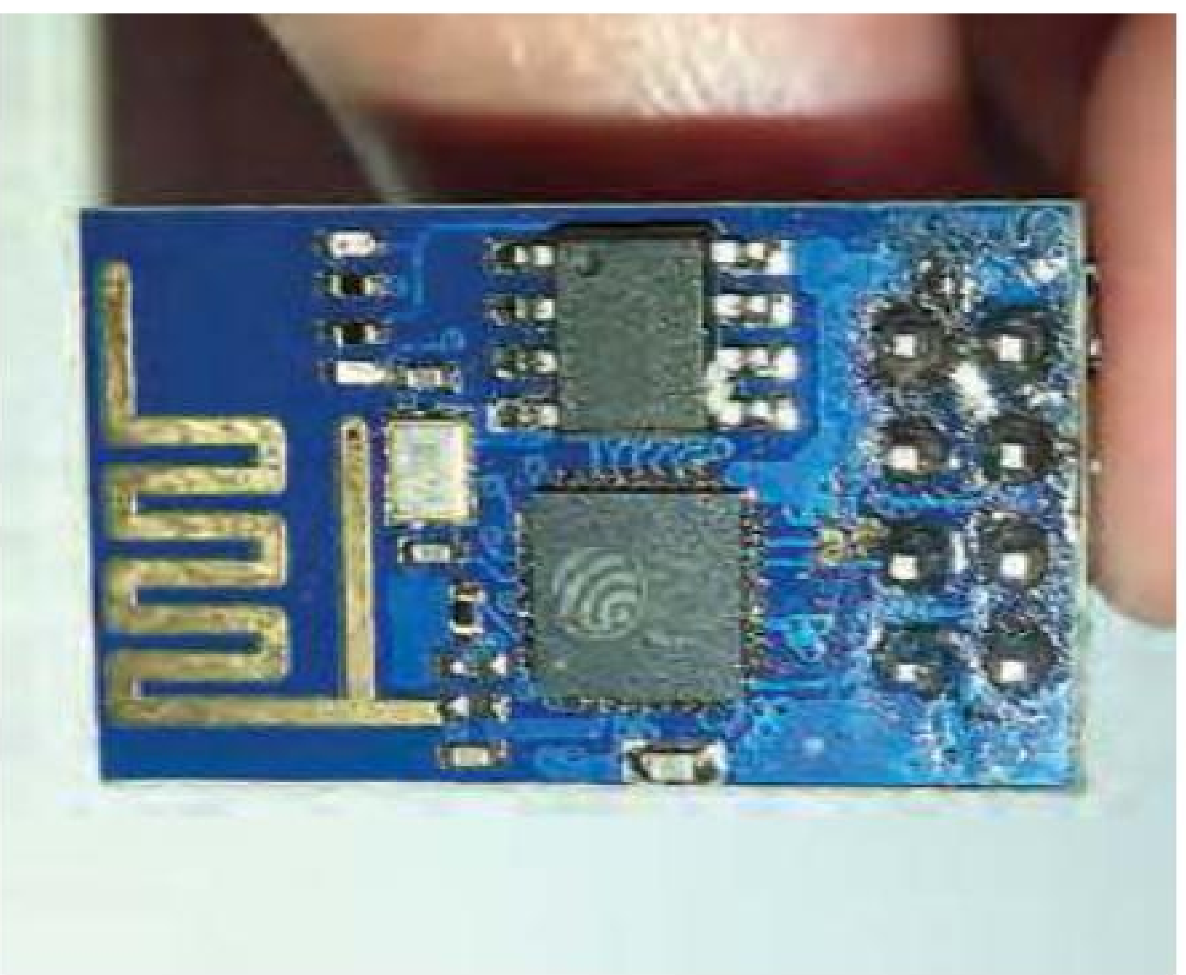
NTP always gives UTC or Universal Coordinated Time. This is the modern, more accurate version of Greenwich Mean Time, which differs from GPS time by (currently) 18 seconds due to the fact that the GPS satellites are not adjusted for leap seconds when they occur.

However, the GPS data stream does include information about how many leap seconds have occurred, so this can be corrected for.

Most GPS receivers can use this information and so give the correct UTC time, but some receivers don't apply the leap second change at the right time. This means that using NTP may actually be more accurate than some GPS receivers.

```
$GPRMC,013115.000,A,3345.6276,S,15116.8171,E,0.00,157.
35,140218,,,A*76
$GPGSA,A,3,05,31,25,29,02,,,,,,,,2.22,2.02,0.92*02
```

Fig.1: an example of typical RMC and GSA sentences from a real GPS receiver. The RMC sentence provides basic fix data such as latitude, longitude, speed, heading, and most importantly, date and time. In this case, the UTC time is 1:31:15am and the date is 14/02/2018.



Here's an alternative ESP8266 module, the ESP-01 (available on eBay and elswhere). It's smaller, but it's not quite as easy to program *in situ.* We have an article describing this module in detail on page 32 of this issue.

Features and specifications:

- * Uses low-cost ESP8266 Wi-Fi module
- * Comparable in size to a GPS module
- * Little or no assembly required
- * Generates standard GPS NMEA data, including time, date, position and signal validity
- * Also produces 1PPS pulses (D1 version only)
- * Automatically fetches NTP time from Internet servers
- * Provides approximate location, for clocks with location-based time zone support
- * Adjustable baud rate
- * Configured via serial port
- * Produces dummy status sentences, for debugging
- * Power supply: ~70mA at 3.0-5.5V

ESP8266 module

The small size of the ESP8266 module means that it can function as a direct drop-in replacement for many GPS modules.

There are quite a few different ESP8266-based modules available. Our preference is for the WeMos D1 Mini, which includes an onboard USB/serial converter to simplify programming, as well as a 5V regulator, allowing it to be used with both 5V and 3.3V power supplies.

Other modules, like the slightly smaller ESP-01 can also be used, but you will need a USB-serial converter to program it and pull-up resistors are also required to get it to operate in the correct mode. We'll show you how to use either module for this project.

The features of the module that we are using are the Wi-Fi connectivity, serial port and also the onboard LED to report some status information. While the small PCB antenna on this module doesn't have a long range, it's expected that it will be used indoors (where GPS isn't available) and probably not too far from a router.

Circuit diagram

The circuit diagram for the ESP8266 WeMos D1 Mini module is shown in Fig.2 and its pinout is shown in Fig.3 and Fig.4. Since this is a pre-built module which does pretty much everything we need it to do, there's no additional circuitry required. We simply feed power into the GND and 3V3 pins and the emulated GPS serial data appears at the TX pin.

If your clock supplies 5V to the GPS module then you can feed this into the 5V pin instead. The onboard regulator then derives the 3.3V supply, which powers the module.

Regardless, the serial data output will have a 3.3V swing, but this is true of most GPS modules (even if they run off 5V) so the clock should not have any problem with this. (5V micros can normally accept 3.3V logic levels at their digital inputs.)

You can also use the smaller ESP-01 Module, but it cannot easily be programmed as-is. You will need a breadboard, some jumper wires and a few resistors so that you can program it. You will also need to add some components to the board before mounting it in the clock, so that it will operate normally.

The ESP-01 also does not include a 3.3V regulator, so the host circuit will have to supply it with 3.3V or thereabouts (3.0-3.6V is acceptable).

Programming it

Regardless of which module you're using, you need to install the Arduino IDE and the ESP8266 processor add-on so that you can upload the code to it. If you haven't already done this for a previous project, use the following steps – and if you do already have this software installed, check to make sure you have the latest version.

First, install the most recent version of the Arduino IDE on your PC, if you don't already have it. This can be downloaded for free: **www.arduino.cc/en/Main/Software**

Next, install the ESP8266 board files. This is also a free download, but it's quite large and will take a while. To do this, open up preferences in the Arduino IDE and under 'Arduino Board Manager URLs', enter: **http://arduino.esp8266.com/stable/package_esp8266com_index.json** (as shown in Fig.6).

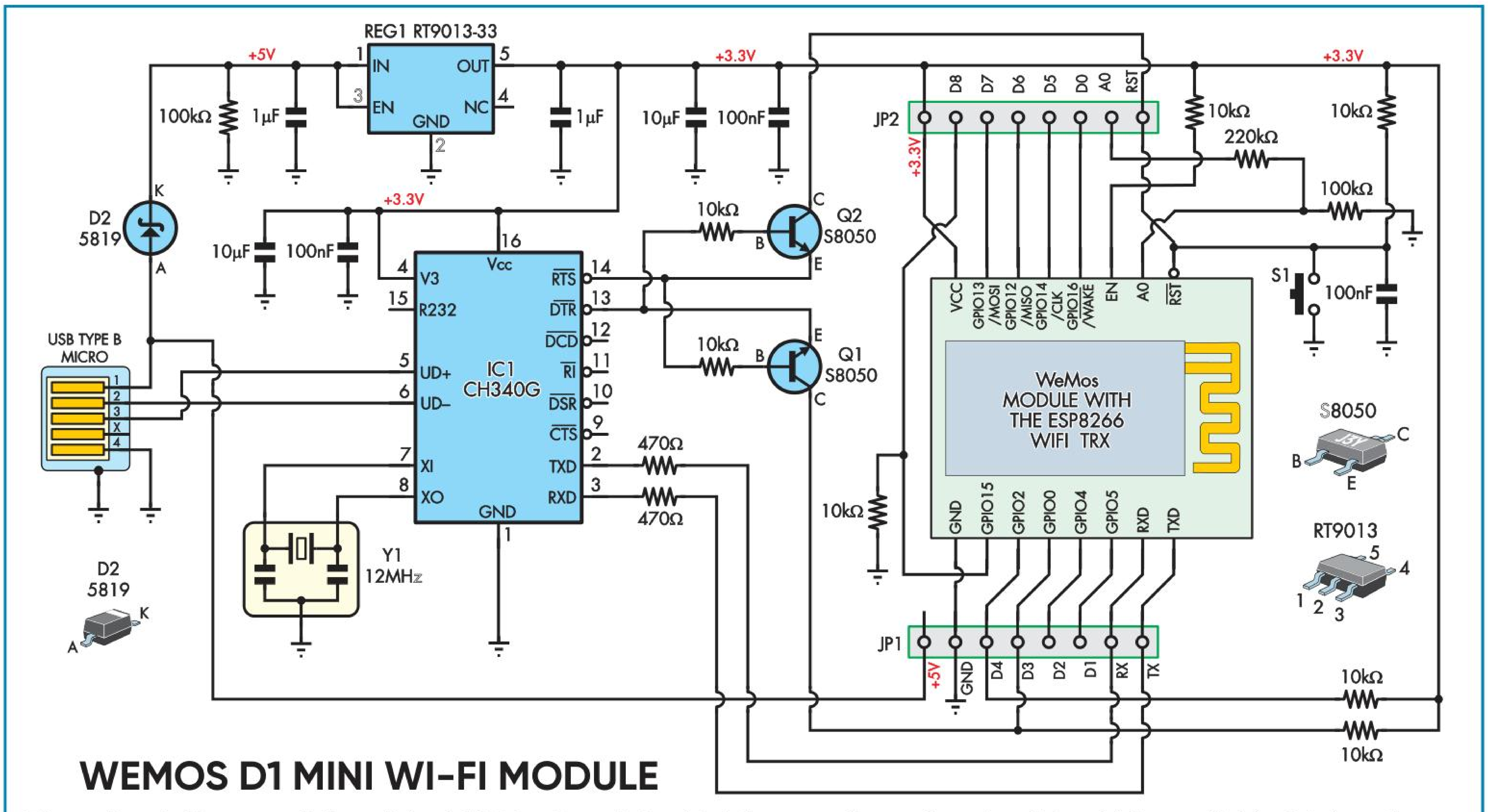

REG1 RT9013-33
+5V
IN
OUT
EN
GND
NC
1
2
3
4
5
+3.3V
100kΩ
1μF
1μF
10μF
100nF
JP2
D8
D7
D6
D5
D0
A0
RST
10kΩ
220kΩ
10kΩ
100kΩ
+3.3V
K
A
D2
5819
10μF
100nF
16
Vcc
V3
R232
IC1
CH340G
UD+
UD–
XI
XO
GND
RTS
DTR
DCD
RI
DSR
CTS
TXD
RXD
14
13
12
11
10
9
2
3
10kΩ
B
C
E
Q2
S8050
10kΩ
Q1
S8050
470Ω
470Ω
USB TYPE B MICRO
X
Y1
12MHz
VCC
GPIO13 /MOSI
GPIO12 /MISO
GPIO14 /CLK
GPIO16 /WAKE
EN
A0
RST
WeMos MODULE WITH THE ESP8266 WIFI TRX
GND
GPIO15
GPIO2
GPIO0
GPIO4
GPIO5
RXD
TXD
S1
100nF
S8050
RT9013
J3Y
JP1
+5V
GND
D4
D3
D2
D1
RX
TX
WEMOS D1 MINI WI-FI MODULE

Fig.2: circuit diagram of the original WeMos D1 mini, which has now been cloned and is widely available. It's based on an ESP8266 Wi-Fi module with onboard processor, but contains extra circuitry to make it easier to program and use.

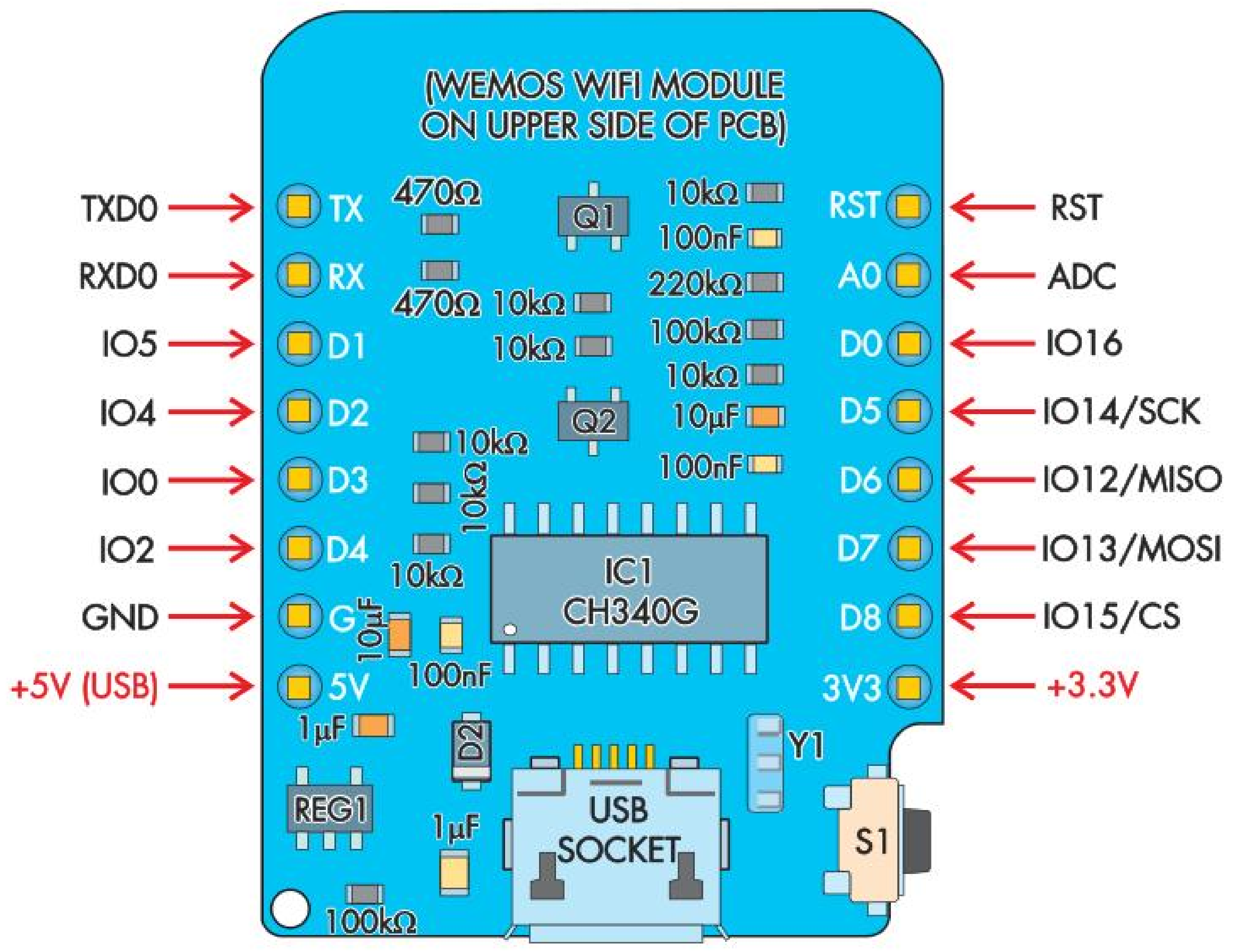


Fig.3: there are several different versions of the D1 Mini board but they are all suitable for this project and have the same pin-out, as shown here. The one we used (a common clone) looks like this but there may be slight variation in the components on the board.

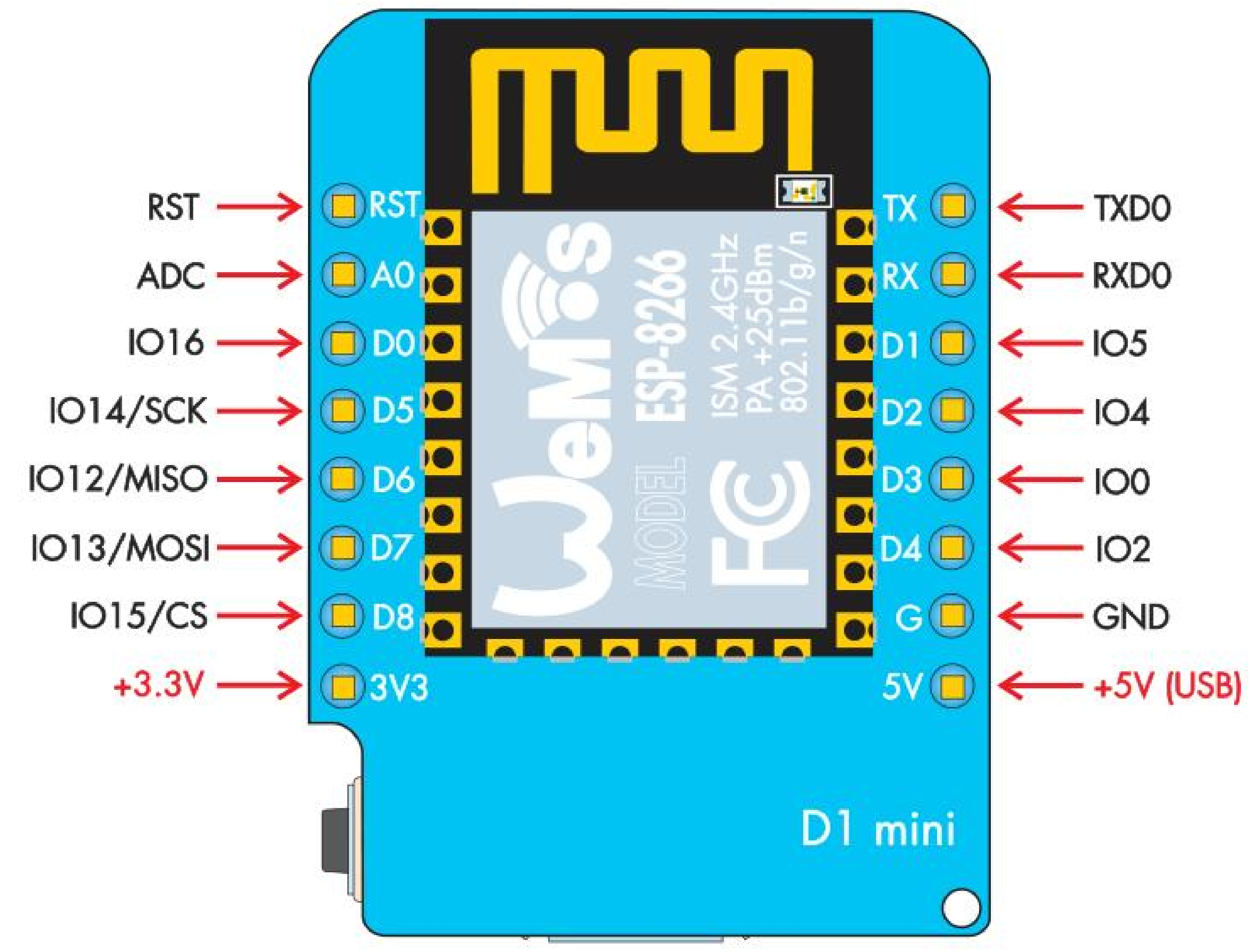


Fig.4: the only part mounted on the the top side of the D1 Mini module is the ESP8266 sub-module, which contains the IC itself plus a few passive components inside a metal shield can. This is the side normally visible when the module is plugged into another board.

Hit OK, then go to Tools → Boards → Board Manager, type in 'esp8266' in the search box, click on the entry which appears below and then click on the 'Install' button (see Fig.7). This will result in around 160MB of compilers and associated files being downloaded and installed on your computer.

There are two main build options, so we'll run through the easier option first. This is using the D1 Mini module. Go to Tools → Board menu and select the 'WeMos D1 R2 & mini' entry. There are no additional libraries to install, as the basic Wi-Fi feature libraries are installed with the ESP8266 processor add-on.

Using a micro-USB cable, plug the D1 Mini module into your PC. Check the ports under Tools → Ports to see that the driver is installed and select the port. If it is not installed, the driver can be downloaded from: **https://wiki.wemos.cc/downloads**

Open the .ino sketch file (downloaded in a ZIP from the *PE*/*EPE* website) and select Sketch → Upload. If everything completes successfully, you can jump ahead to the Setup section.

Using the ESP-01 module

The ESP-01 module is less than half the size of the D1 Mini, which means it can't fit a lot of the nice features of the larger board (such as the onboard USB/serial converter). Still, it isn't too difficult to build a rig for programming this tiny module. You will need a separate USB/serial converter with a 3.3V supply output, as the ESP-01 will not like 5V! For example search eBay for 'CP2102-based USB/TTL serial converter' – at the time of writing eBay item 333014805451. See Fig.5 for the connection diagram.

Connect one male/female jumper lead to each of the ESP-01's pins except for GPIO2, and run the other end to one edge of the breadboard. We used red for V_{CC}, black for GND, orange for TX, yellow for RX, green for RST, blue for GPIO0 and mauve for CH_PD ('Power down'). The mauve lead for CH_PD can connect to the same row as V_{CC}, as CH_PD needs to be pulled up to Vxx for the module to do anything.

Connect another four male/female jumper leads to the USB-serial converter and then connect these to the ESP-01 via the breadboard as follows: red lead to 3.3V, black to GND, orange (from TX on the ESP-01) to RXD on the USB/serial converter, and similarly, yellow (from RX on the ESP-01) to TXD on the USB/serial converter.

The ESP-01 module needs some pull-up resistors for correct operation, so connect a 10kΩ resistor from the V_{CC} row to the RST row (between the green and red jumper leads), and another 10kΩ resistor from the V_{CC} row to the GPIO0 row (between red and blue jumper leads). See Fig.5 for details.

Finally, using male-to-male jumpers, add flying leads to the RST and GPIO0 rows (green and blue). These are now our reset and programming jumpers, and we plug them into the GND row to activate them. If you prefer, you could even fit some tactile pushbuttons to the breadboard if you are going to be using this setup more than once.

To reset the ESP-01, touch the green lead to GND. To enter UART upload (programming) mode, hold the blue wire against GND, then briefly touch the green wire to GND, then release the blue wire. You can even touch the green wire to the blue wire (while it is against GND) to ensure everything happens in the right sequence.

Another trick you could use if you want to make the set-up more permanent is to (carefully!) glue the sockets that are plugged into the ESP-01 together to form a single large socket which can be removed as one piece from the ESP-01. If you are using a cyanoacrylate type adhesive (Super Glue), gently separate the sockets to allow the glue to penetrate, apply a small amount away from the ESP-01, then firmly squeeze them together until the glue takes.

Now, having built our programming rig, we can upload the code to the ESP-01.

Click Sketch → Upload in the IDE and while the sketch is compiling, touch GND to the blue wire, then green and then release the green and release blue. The ESP-01 will

Parts list – NTP Time Source

1 D1 Mini ESP8266 module or
1 ESP-01 module

To program the ESP-01, add:
1 USB/serial converter (see text)
1 small breadboard
2 10kΩ 0.25W resistors (1% or 5%)
2 male-to-male jumper wires (to suit breadboard)
11 male-to-female jumper wires (to suit breadboard)

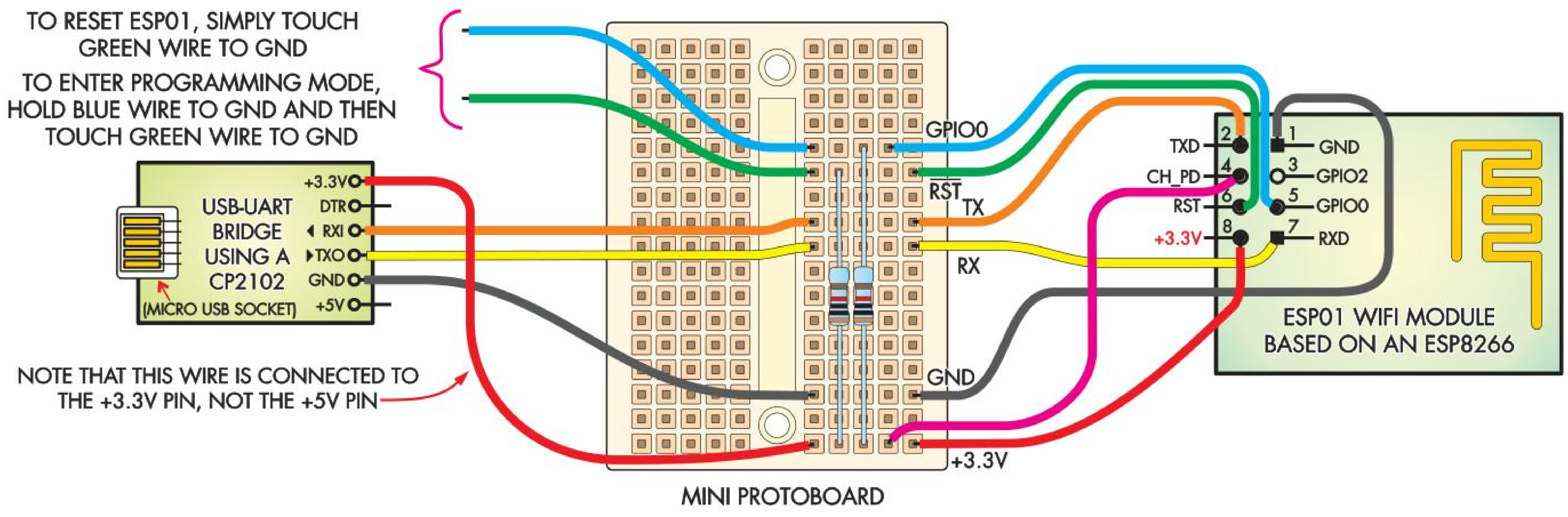

TO RESET ESP01, SIMPLY TOUCH GREEN WIRE TO GND
TO ENTER PROGRAMMING MODE, HOLD BLUE WIRE TO GND AND THEN TOUCH GREEN WIRE TO GND
USB-UART BRIDGE USING A CP2102
(MICRO USB SOCKET)
+3.3V
DTR
RXI
TXO
GND
+5V
NOTE THAT THIS WIRE IS CONNECTED TO THE +3.3V PIN, NOT THE +5V PIN
GPIO0
RST
TX
RX
GND
+3.3V
MINI PROTOBOARD
TXD
CH_PD
RST
+3.3V
2
4
6
8
1
3
5
7
GND
GPIO2
GPIO0
RXD
ESP01 WIFI MODULE BASED ON AN ESP8266

Fig.5: this is how the ESP-01 module is connected for programming. Note the two loose wire 'ends', which are used to put the module into programming mode.

stay in programming mode until it is reset or a sketch is successfully uploaded, in which case it will run the uploaded sketch.

Any errors will appear in the bottom pane of the Arduino IDE window. If you get errors like 'error: espcomm_upload_mem failed', this is because the computer cannot send data to the ESP-01. In this case, try the blue/green sequence again. Usually, the blue LED on the module will blink on and off in 'run' mode, but will only briefly flicker once in programming mode, so if the LED is blinking, you may not be in programming mode.

We've found that uploading to the ESP8266-based devices is sometimes less reliable than other devices, so it may simply be a case of trying a few times.

Set-up

With the sketch completely uploaded to the device, open the Serial Monitor at 9600 baud (you can do this via the Tools menu or, in Windows, the key combination CTRL+SHIFT+M). The program will transmit its current baud rate at 9600 baud before running, so if you see a different number or garbage output in the Serial Monitor, check the displayed baud rate and use that instead.

Within a few seconds, there should be a stream of data on the screen, similar to Fig.8. The lines beginning with '$GPRMC' and '$GPGSA' are our emulated GPS (NMEA) data, while the '$ESP82' lines are debugging information so that we can follow what our NTP-based GPS Time Source is doing.

These two groups of three lines show the data from a configured module that has already connected to a Wi-Fi network. You can see that it updates its time, latitude and longitude between the first and second group of sentences (it really is that quick!).

You will probably see something that looks like the first group repeated, as your unit will not be connecting to a Wi-Fi network just yet.

To enter the configuration menu, type '~' and press enter on the Serial Monitor. You will need to have the serial monitor set up to produce carriage return (CR) or carriage return/line feed (CR/LF) at the end of each line, as the menu looks for CR on some commands; this happens by default.

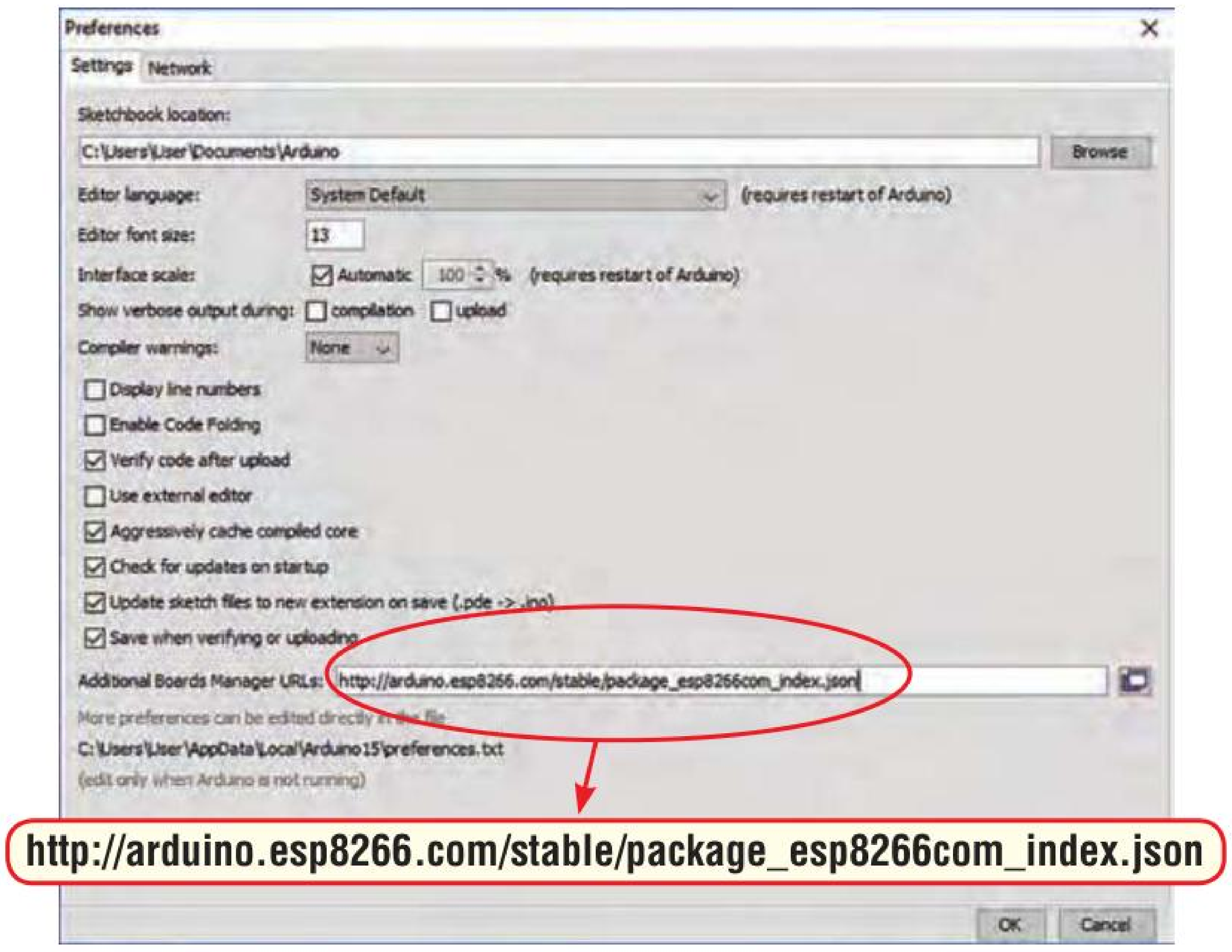
The menu will appear, as shown in Fig.9. You will need to configure options three and four to suit your local Wi-Fi network by pressing '3' and Enter, followed by your Wi-Fi network's SSID name and then press Enter. Then type '4' and Enter, followed by the password and Enter.

As you might imagine, the password is saved in a non-secure fashion and can easily be viewed by anyone who has access to the module, so be careful who you give it to.

The NTP server and dummy coordinates should not need to be changed, but this can be done in a similar fashion if necessary.

The dummy coordinates correspond to Sydney, Australia, so should be a good default if you are using the *High Visibility 6-Digit LED GPS Clock* there! If you are using the *GPS-synchronised Analog Clock Driver*, these don't matter, as the time zone is set in the PIC on the driver PCB.

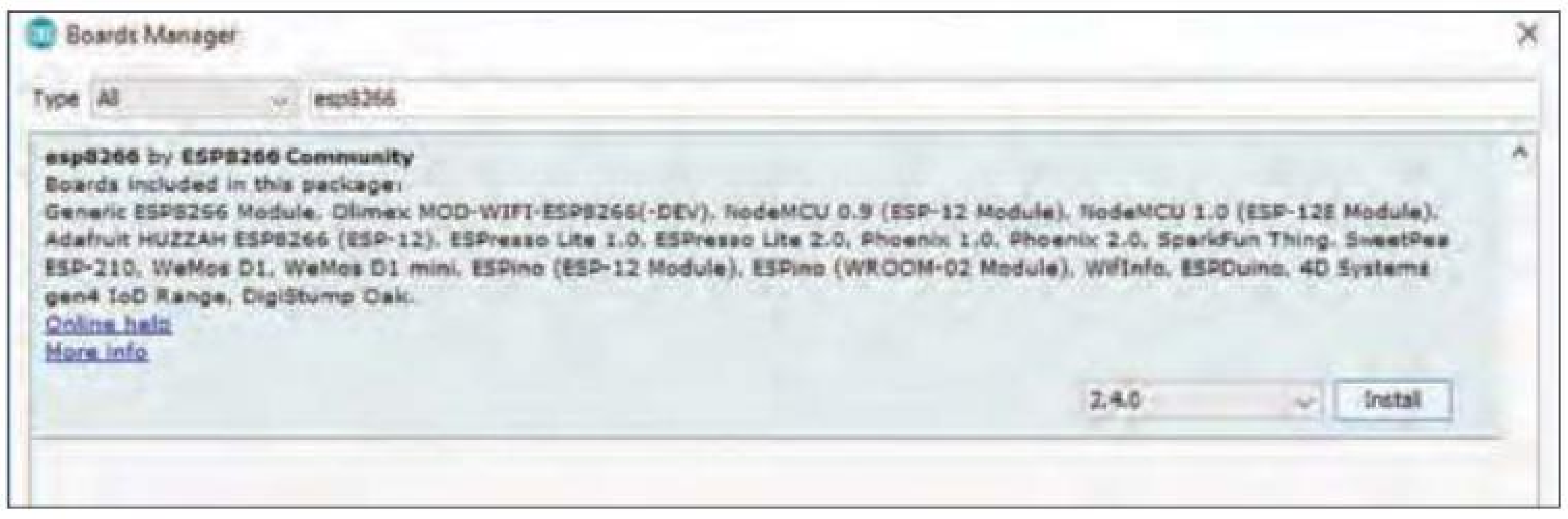
In any case, the unit should get a reasonably accurate latitude and longitude from the IP web service. It's only in the case that this fails that the defaults are used.



Sketchbook location:
C:\Users\User\Documents\Arduino
Editor language: System Default (requires restart of Arduino)
Editor font size: 13
Interface scale: ☑ Automatic 100 % (requires restart of Arduino)
Show verbose output during: ☐ compilation ☐ upload
Compiler warnings: None
☐ Display line numbers
☐ Enable Code Folding
☑ Verify code after upload
☐ Use external editor
☑ Aggressively cache compiled core
☑ Check for updates on startup
☑ Update sketch files to new extension on save (.pde -> .ino)
☑ Save when verifying or uploading
Additional Boards Manager URLs: http://arduino.esp8266.com/stable/package_esp8266com_index.json
More preferences can be edited directly in the file
C:\Users\User\AppData\Local\Arduino15\preferences.txt
(edit only when Arduino is not running)

http://arduino.esp8266.com/stable/package_esp8266com_index.json

Fig.6: before you can install the ESP8266 Board file, you need to tell the Arduino IDE where to find it. You do that in the Preferences dialog, as shown here.



Type All esp8266

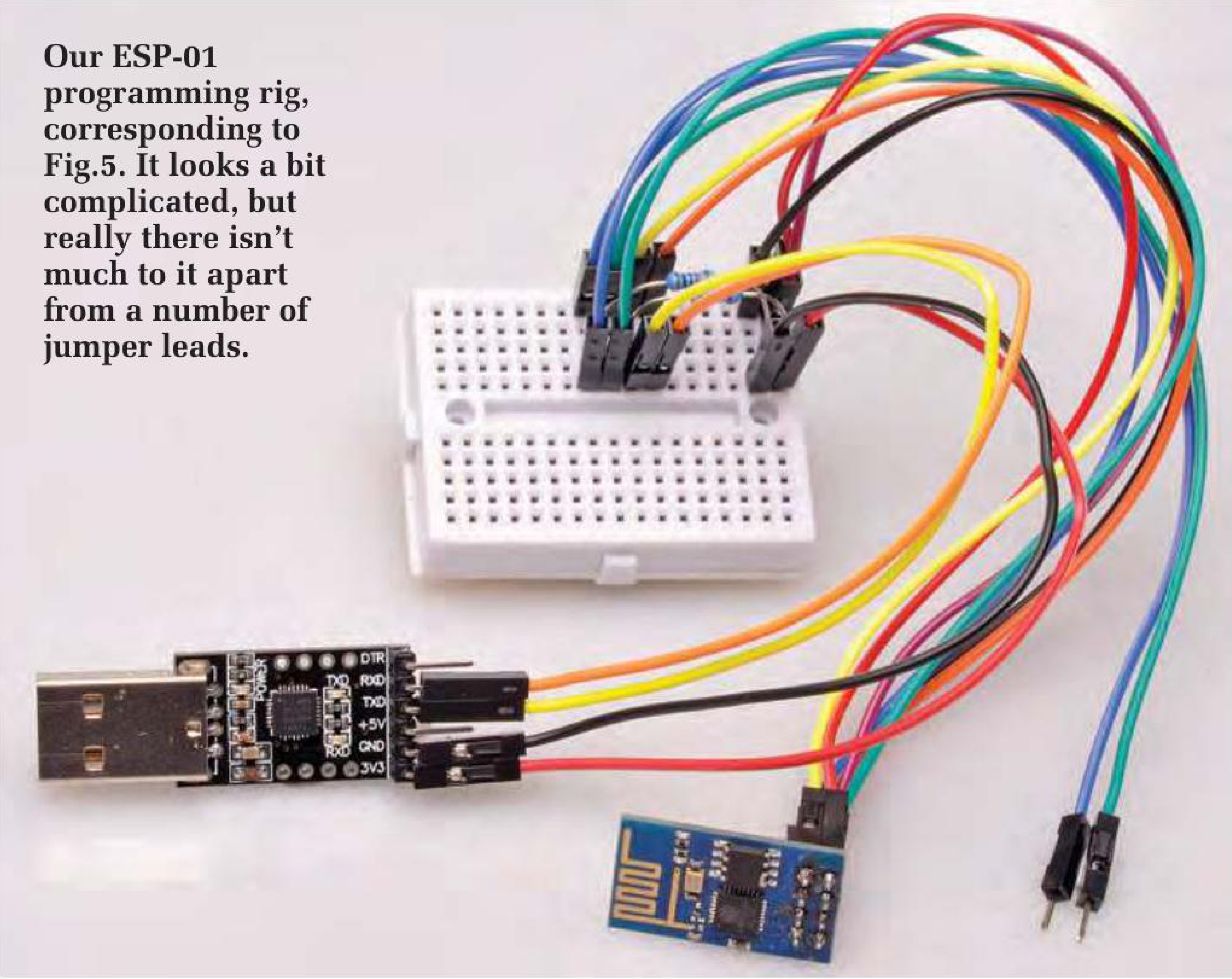
esp8266 by **ESP8266 Community**
Boards included in this package:
Generic ESP8266 Module, Olimex MOD-WIFI-ESP8266(-DEV), NodeMCU 0.9 (ESP-12 Module), NodeMCU 1.0 (ESP-12E Module), Adafruit HUZZAH ESP8266 (ESP-12), ESPresso Lite 1.0, ESPresso Lite 2.0, Phoenix 1.0, Phoenix 2.0, SparkFun Thing, SweetPea ESP-210, WeMos D1, WeMos D1 mini, ESPino (ESP-12 Module), ESPino (WROOM-02 Module), WifInfo, ESPDuino, 4D Systems gen4 IoD Range, DigiStump Oak.
2.4.0

Fig.7: this shows how you install the ESP8266 'core' files in the Arduino Board Manager. This process lets you compile and upload code to ESP8266-based boards, including the ESP-01 and WeMos D1 Mini.

Finally, press ‘9’ and then Enter to save, then press the reset button on the side of the D1 Mini to load the new defaults. You should see a valid IP address appear after the second comma of the ‘$ESP82’ sentence if the Wi-Fi connects successfully. See Fig.8 for more detail on this.

Checking the ‘$GPRMC’, ‘$GPGGA’ and ‘$GPGSA’ sentences should reveal valid data, including the current (UTC) time and date after ‘$GPRMC’. If everything seems to be working here, we can connect it up to our clock.

The D1 Mini also has an onboard LED to help set-up and troubleshooting. While it is looking for a Wi-Fi network at start-up, the LED is on solidly – so if the LED lights up and never goes out, the unit is not connecting to your Wi-Fi network. After this, the LED will blink every time data is transmitted, which should be once per second.



Our ESP-01 programming rig, corresponding to Fig.5. It looks a bit complicated, but really there isn’t much to it apart from a number of jumper leads.

Configuring the ESP-01

As well as needing the right combination of pull-ups and pull-downs to be programmed, the ESP-01 will also need to be configured to run correctly before connecting it to a clock. Fortunately, this is easily done by adding solder bridges to some of the pins to connect them to the correct voltage levels.

Soldering the pins simply prevents the ESP-01 from entering programming mode, so it can still be configured via the setup menu on the serial port if necessary.

Carefully run a bridge of solder between the 3.3V pin (the top left pin when looking at the top of the board, pins at the top), CH_PD, RST, GPIO2 and GPIO0 (the four centre pins). This effectively forces the ESP-01 into run mode every time it is powered up. We found it easiest to bridge out the four centre pins, then tilt the module to allow the bead of solder to reach the 3.3V pin.

See the photo on the next page for how the ESP-01 should look after it has been bridged. Alternatively, you could solder a couple of short lengths of hookup wire to join the pins.

To connect it to the clock, plug jumper leads into 3.3V (top left), GND (bottom right) and TX (above GND). From now on, the ESP-01 can be treated like the D1 Mini and these are the only three connections you need. Note that with the ESP-01 module, the blue LED is connected to the TX pin, so it will flicker to indicate data is being transmitted but will not solidly stay on while the module is attempting to connect to Wi-Fi, as with the WeMos board.

Connecting to the *GPS-synchronised Analogue Clock Driver*

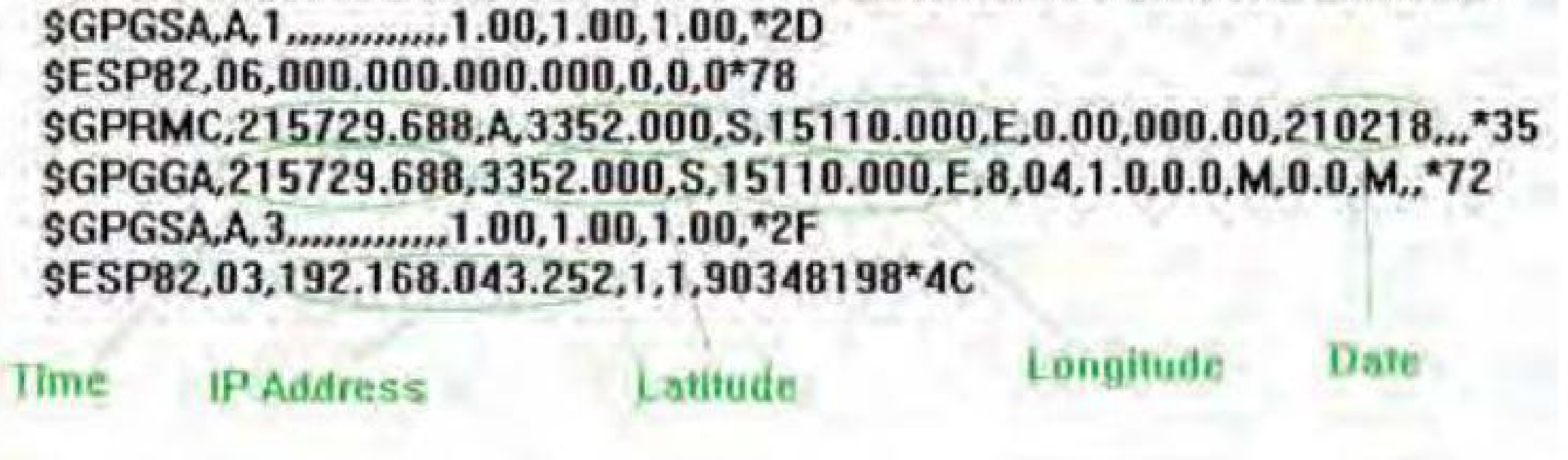
There are only three connections needed to work with the *GPS-synchronised Analogue Clock Driver* from February 2018: power (3.3V), ground and the serial data. Remove the battery from the *Clock Driver*, ensure that JP1 is set to the 3V position, then wire the unit up to the GPS module header. See the top photo opposite for details.

This means connecting the 3.3V pin on the D1 Mini to the V_{CC} pin on the clock, Ground (‘G’) to GND and TX to TX. We used some jumper socket lead off-cuts to wire up our D1 Mini, so it’s easier to remove in future if necessary (for example, if we need to configure it to a different Wi-Fi network).

You’ll see in the photo that we’ve actually connected 3.3V to the ‘EN’ pad on the PCB, because it’s directly connected to V_{CC} on the reverse of the clock PCB and it means that the wires don’t need to cross.

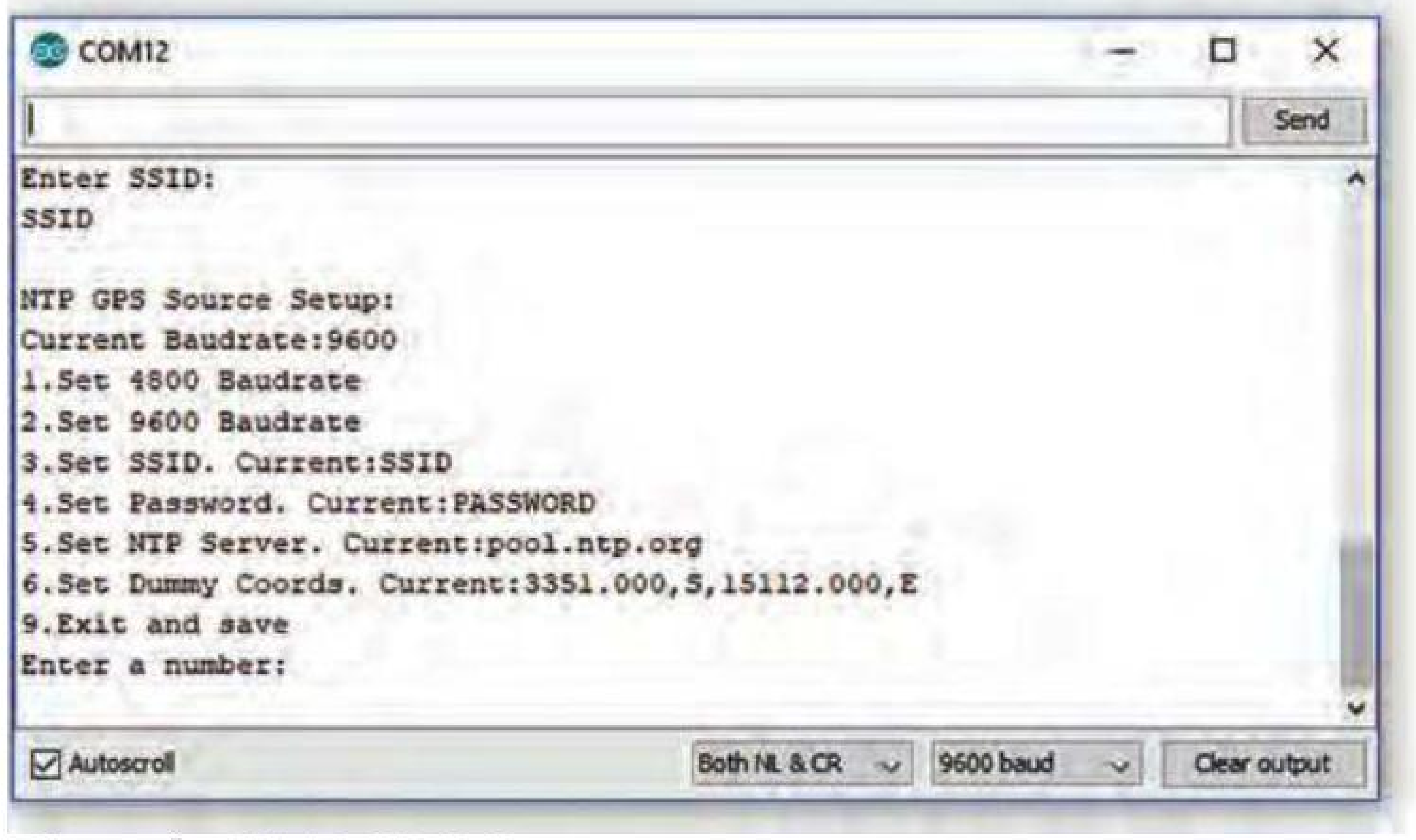
Set the hands of the clock to 12, and re-insert the cells. You should see the STARTUP LED on the *Clock Driver* flash once, then twice as it powers up the D1 Mini. If the D1 Mini’s LED does not light, check the wiring connections.

The LED should go out again in a few seconds as it connects to Wi-Fi, and provided the Internet connection is good and the NTP servers are online, the STARTUP LED on the *Clock Driver* will flash four times and it will start double-stepping towards the correct time.



```
$GPRMC,000002.000,V,3351.000,S,15112.000,E,0.00,000.00,200718,,,*29
$GPGGA,000002.000,3351.000,S,15112.000,E,0,04,1.0,0.0,M,0.0,M,,*75
$GPGSA,A,1,,,,,,,,,,,,,1.00,1.00,1.00,*2D
$ESP82,06,000.000.000.000,0,0,0*78
$GPRMC,215729.688,A,3352.000,S,15110.000,E,0.00,000.00,210218,,,*35
$GPGGA,215729.688,3352.000,S,15110.000,E,8,04,1.0,0.0,M,0.0,M,,*72
$GPSA,A,3,,,,,,,,,,,,,1.00,1.00,1.00,*2F
$ESP82,03,192.168.043.252,1,1,90348198*4C
```

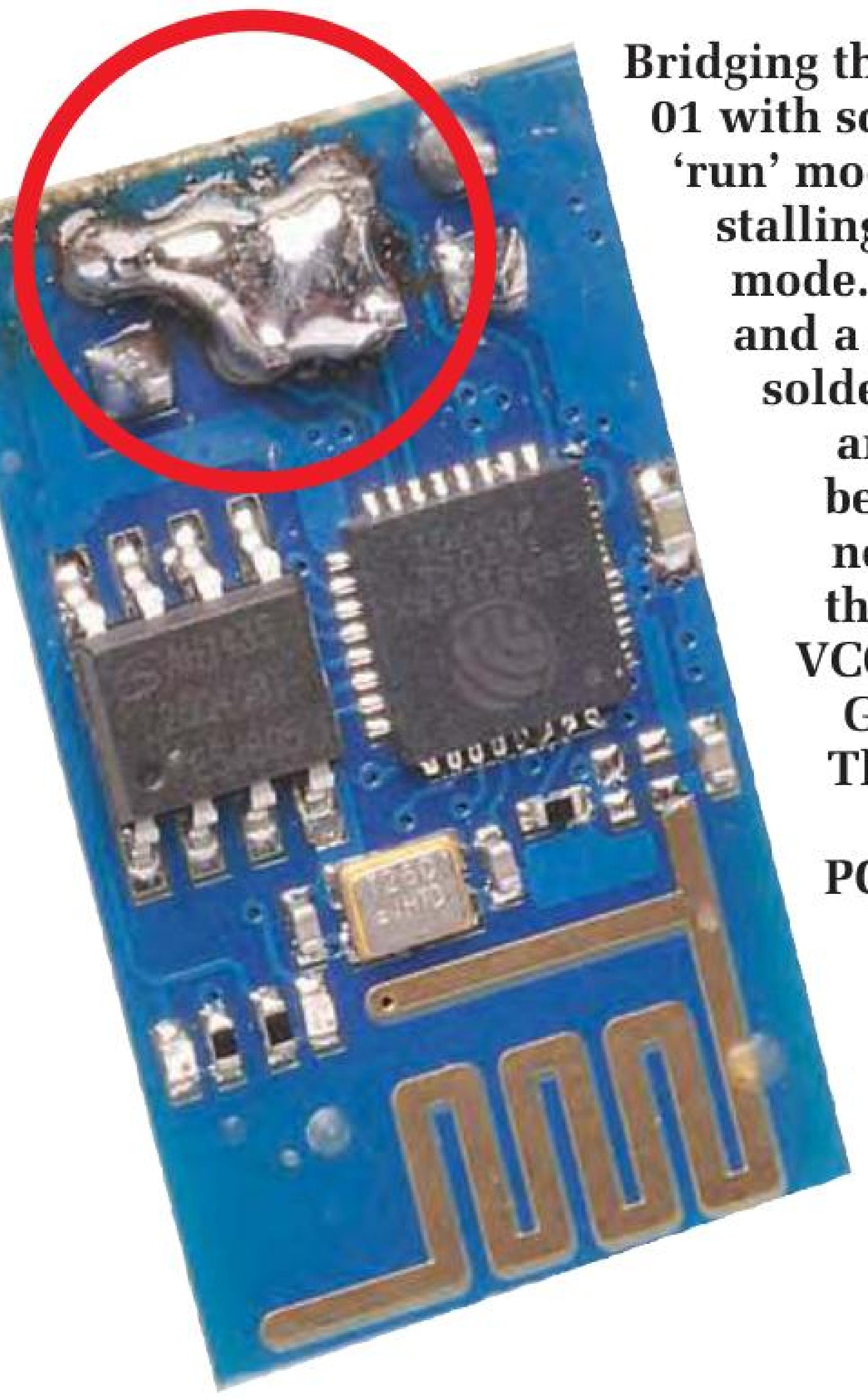
Fig.8: sample output from the completed NTP/GPS Adaptor unit. The GPRMC, GPGGA and GPGSA sentences mimic those produced by a GPS receiver (hence the GP prefixes) while the ESP82 sentence contains our debugging data. You can see that the unit acquired a Wi-Fi IP address (192.168.43.252) between the first and second instances.



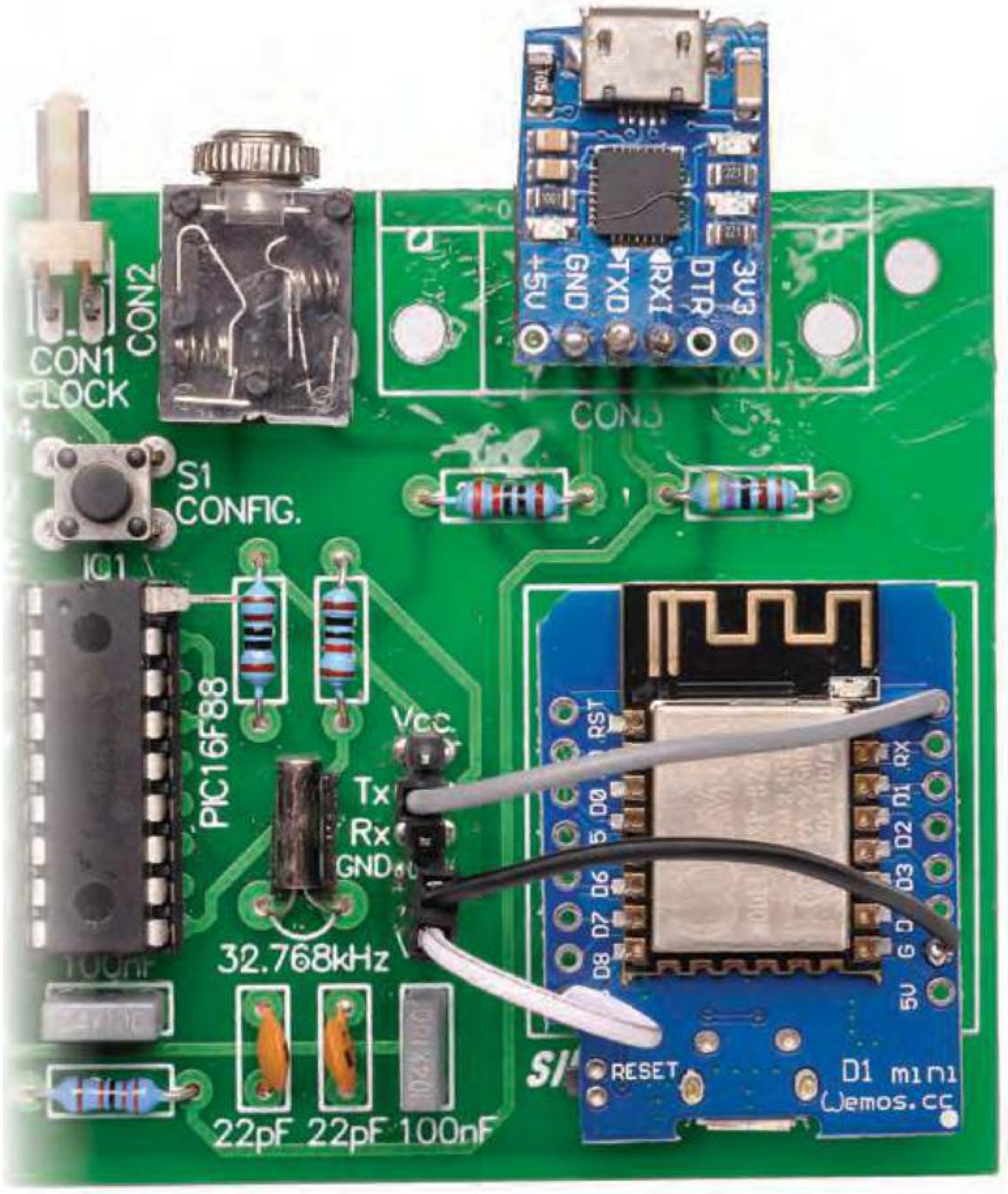
```
Enter SSID:
SSID

NTP GPS Source Setup:
Current Baudrate:9600
1.Set 4800 Baudrate
2.Set 9600 Baudrate
3.Set SSID. Current:SSID
4.Set Password. Current:PASSWORD
5.Set NTP Server. Current:pool.ntp.org
6.Set Dummy Coords. Current:3351.000,S,15112.000,E
9.Exit and save
Enter a number:
```

Fig.9: the NTP GPS Source set-up menu.



Bridging the pins of the ESP-01 with solder forces it into 'run' mode and prevents it stalling in UART upload mode. With a bit of care and a solder sucker, the solder can be removed and the ESP-01 can be reprogrammed if necessary. The pins that are bridged are VCC, CH_PD, GPIO0, GPIO2 and RESET. The copper track at the bottom of the PCB is the on-board antenna.



Only three wires are needed to connect the D1 Mini to the *GPS-synchronised Analogue Clock Driver* and although slightly larger than the GPS Module, the D1 Mini is a great fit for the PCB.

Connecting to the *High Visibility 6-Digit LED GPS Clock*

The set-up for the *High Visibility 6-Digit LED GPS Clock*, from the January and February 2017 issues is similar to that for the *GPS-synchronised Analogue Clock Driver*. Because our prototype unit did not have a 1PPS output (and it is not required by the clock), we did not connect it. If you need it, it's on pin D2 of the Mini.

Ensure that LK1 is set to the 3.3V position and connect +V to 3.3V on the D1 Mini, GND to G and TX to TX, as shown in the photo below.

Power on the clock, and after a few seconds you should see the GPS display indicating that the clock is awaiting a valid GPS signal. Once valid data has been received by the clock, it will go to the normal clock display. Since this clock uses latitude and longitude to set the time zone, incorrect data here may lead to an incorrect time being displayed.

If you find the time is incorrect (especially if it is out by a whole number of hours), the *NTP-based GPS Time Source* may not be providing correct latitude and longitude data, in which case the dummy values may need to be changed.

The NTP-based GPS Time Source updates its time from the NTP servers every hour. We've tried to program it so that it won't 'jump' when that happens; in fact, you probably won't notice it. But for the first few hours, as the drift compensation will not be operational yet, you may notice an occasional slight glitch in the time.

Using it with other clocks and NTP servers

Any device that uses GPS data as its clock source should be able to use this project. With NTP being used so widely, the time provided is quite accurate and the three connections for power, ground and data are usually easy to find.

The default NTP server used in our sketch is actually provided by volunteers who donate their server time to make NTP widely available. For more information, see: **http://www.pool.ntp.org/en/**

As always, servers on the Internet may come and go, and there are alternatives. For example, **nist.time.gov** is provided by the US government, and it was a server we tried while testing the *NTP-based GPS Time Source*. In practice, because the servers are so far away, the round-trip time for our data was too long to maintain accuracy, so a closer server was chosen at: **pool.ntp.org**

This server is actually a large number of servers around the world and the Internet's DNS system tries to point you to a nearby server.

The server can be changed via the configuration menu by pressing '5' and Enter, then entering the URL or IP address of the new server.

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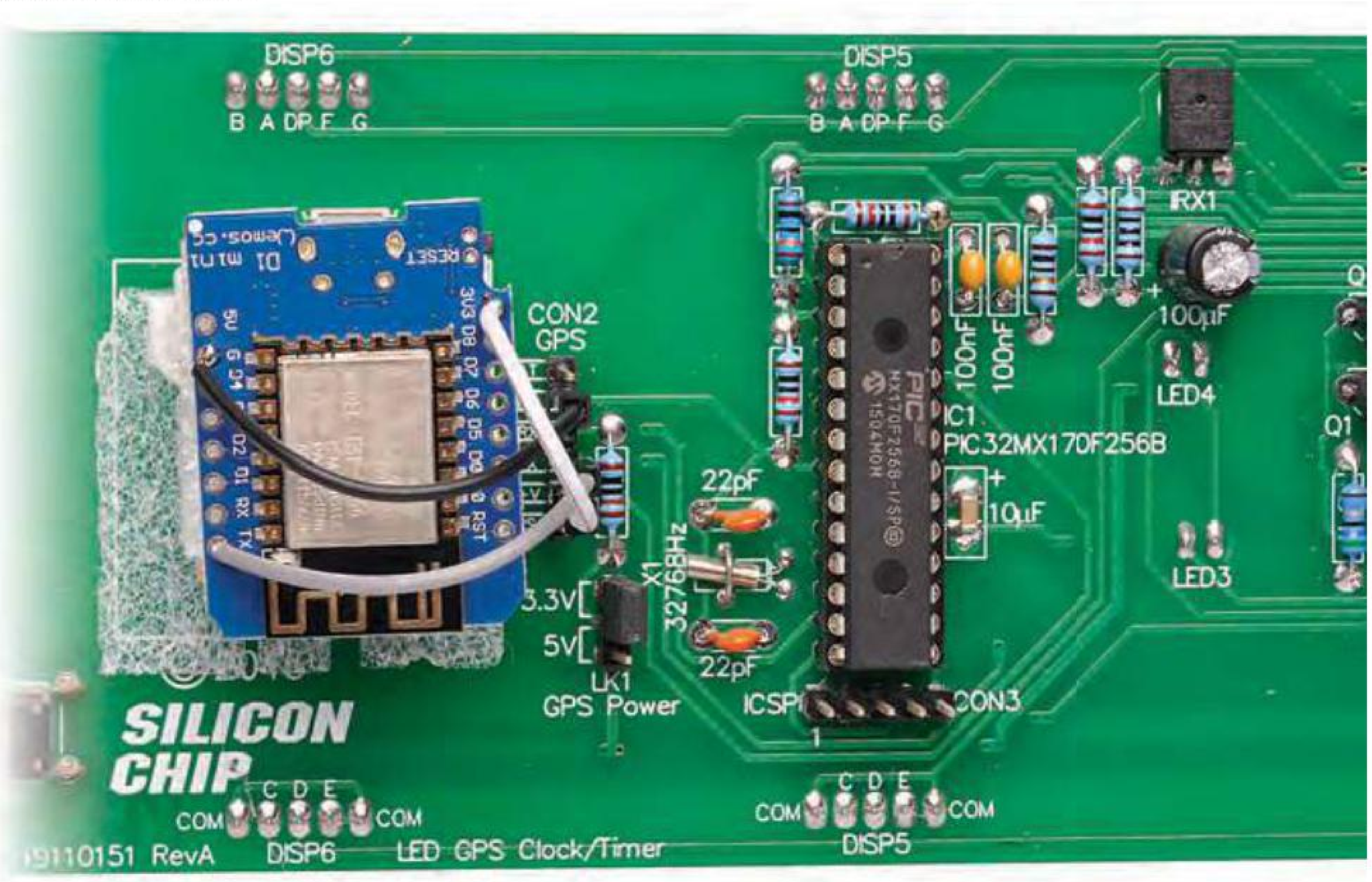


Using a row of header pins makes it much easier to connect our completed unit to the clock. In this case, we only need three pins.

Win a SAM R34 Xplained Pro LoRaWAN Evaluation Kit

Practical Electronics is offering its readers the chance to win a SAM R34 Xplained Pro Evaluation Kit for LoRaWAN development (ATSAMR34-XPRO).

Microchip's SAM R34 Xplained Pro Evaluation Kit is a hardware platform used to evaluate the ATSAMR34 low-power LoRa sub-GHz SiP, designed to enable long-range wireless connectivity while extending system battery life.

The highly integrated LoRa SiP family combines an ultra-low-power 32-bit microcontroller, sub-GHz RF LoRa transceiver and software stack. It is supported by certified reference designs and proven interoperability with major LoRaWAN gateway and network providers, significantly simplifying the entire development process with hardware, software and support. The devices also provide the industry's lowest power consumption in sleep modes, offering extended battery life in remote IoT nodes.

Worth $98.50 (approx £76.50) each

Supported by the Atmel Studio integrated development platform, the kit provides easy access to the features of the ATSAMR34 and explains how to integrate the device in a custom design. This FCC-, ISED- and RED-certified board is not only an evaluation platform, but also an excellent reference design for developing SAM-R34-based LoRa end-node applications.

Atmel Studio support includes predefined application examples. The kit also provides easy access to various features of the ATSAMR34J18B device and offers additional peripherals to extend the features of the board and ease the development of custom designs.

Free-to-enter competition

Microchip
SAM R34 Xplained Pro LoRaWAN Evaluation Kit

How to enter

For your chance to win a SAM R34 Xplained Pro LoRaWAN Evaluation Kit, just visit:

http://page.microchip.com/EPE-SAM-R34.html

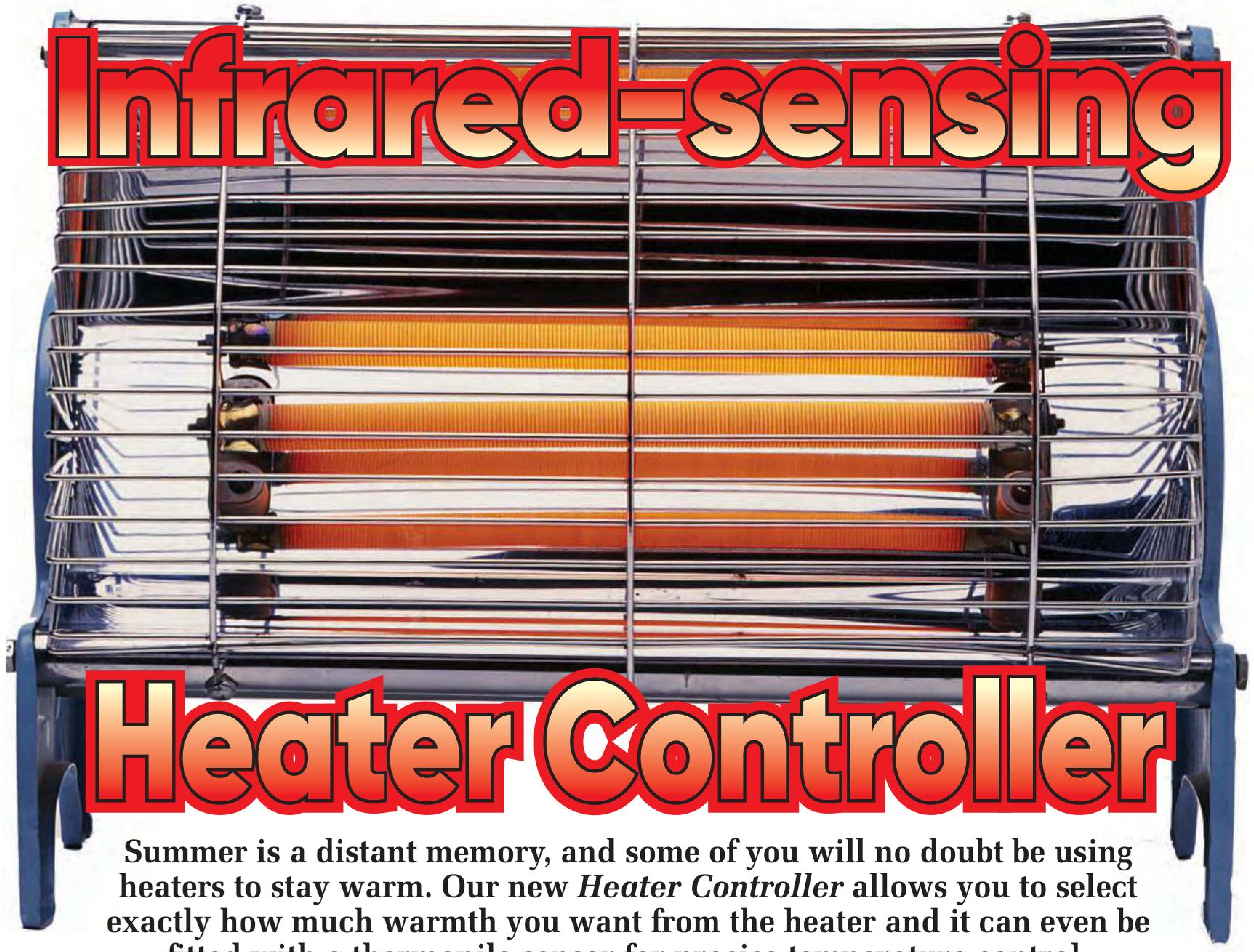
Closing date

The closing date for this offer is 30 April 2019.

December 2018 winners

Ian Williams and Ravi Rao
They each won a Microchip SAM L11 Xplained Pro Evaluation Kit – valued at $22.50

Infrared-sensing Heater Controller



Summer is a distant memory, and some of you will no doubt be using heaters to stay warm. Our new *Heater Controller* allows you to select exactly how much warmth you want from the heater and it can even be fitted with a thermopile sensor for precise temperature control.

Most electric radiators are pretty crude devices: you switch 'em on and they get hot.

But in small rooms, they will quickly get *too* hot and then you will want to switch them off or possibly down a level or two, if they have such a switch.

Most heaters pump out too much heat for a small room, even when they are on the lowest setting. You really need a heat controller. Our new *Heater Controller* is exactly what you want. Think of it as a 'dimmer for radiators'. But it is a lot more than that.

We should note that some heaters, typically oil-filled units, do have a thermostat where the heater switches off when the air temperature reaches a set value and then it switches back on when the heater cools down.

The thermostat is usually mechanical and often makes a clicking noise whenever the switching occurs, and it may also cause a neon or LED to flash on and off at the same time.

That intermittent noise and light may be be disturbing if the heater is used in a bedroom while you are trying to get to sleep. It can also result in a noticeable heating/cooling cycle if you are close to the radiator.

Our new *Heater Controller* has no mechanical switching to cause noises and it incorporates a thermopile infrared sensor so it can maintain a set temperature in a room.

Alternatively, it can be built without the optional infrared sensor so you can use it to simply select the amount of heating that you desire.

We should point out that the *Heater Controller* is ***not suitable*** for fan heaters. At the lower settings the fan will not run and that could cause the unit to over-heat and fail.

How it works

Our *Heater Controller* works by applying an integral (ie, whole) number of full mains voltage cycles to the heater.

by John Clarke

At lower power settings, fewer cycles are applied and for higher power, a greater number are applied. We have included a number of scope grabs to illustrate this switching operation.

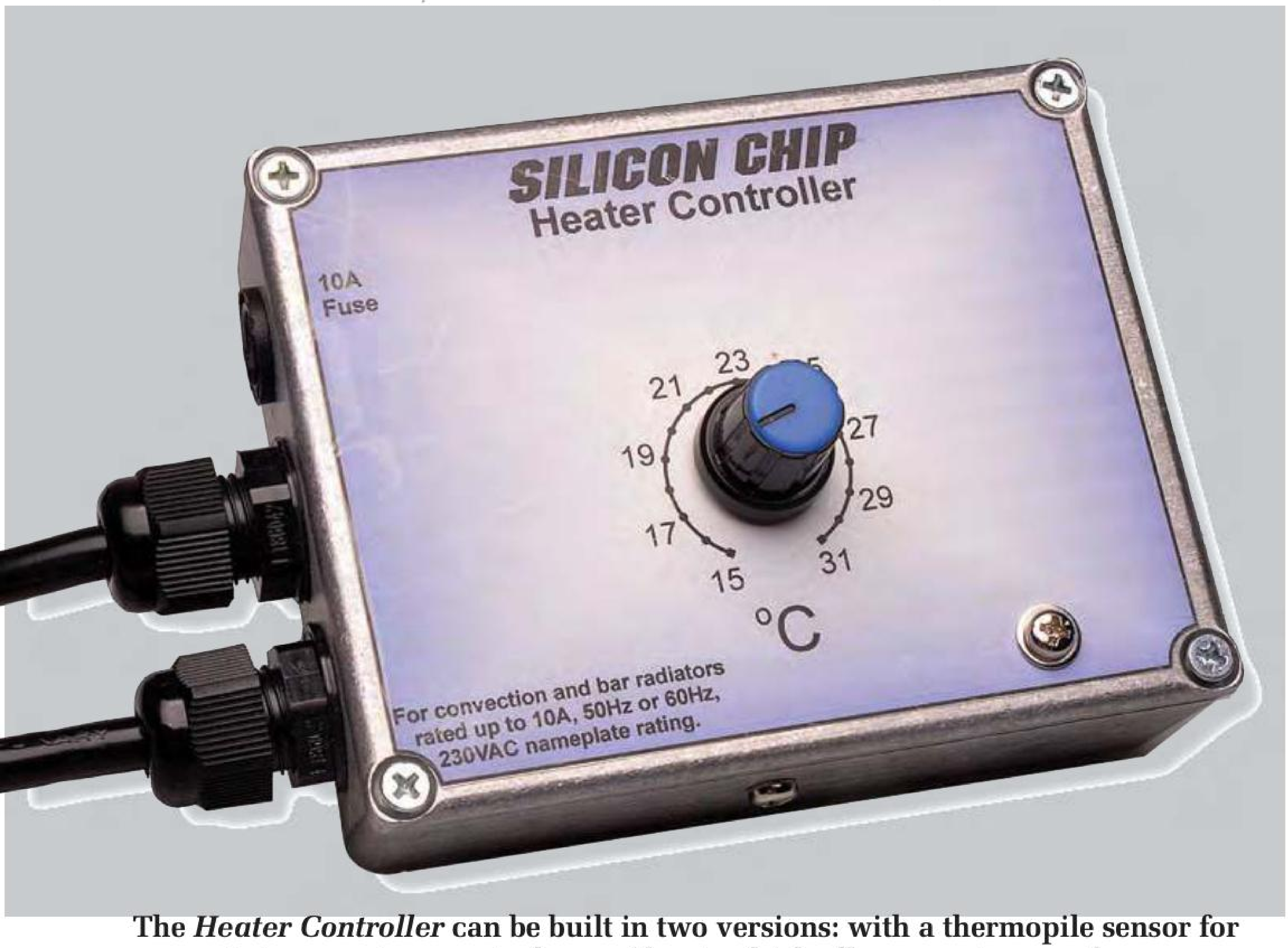
For example, at low power, it may only apply one cycle of 50Hz 230VAC out of every 15. At full power, the mains voltage is on constantly (as if the controller was not present).

It uses a 15-cycle control period, which corresponds to 300ms for 50Hz mains (as in the UK, Australia or New Zealand) or 250ms for 60Hz.

At half power, there are seven or eight cycles of mains voltage applied to the heater out of 15 incoming cycles.

The switching action will not be noticeable with heaters with wound resistance elements, but it will be visible with radiator elements in silica glass tubes and very noticeable in those with halogen lamps. In fact, the flashing of halogen lamps in those heaters will drive you bonkers – don't do it!

The mains voltage is only switched as it passes through zero volts (ie, 'zero-


SILICON CHIP
Heater Controller
10A Fuse
15
17
19
21
23
27
29
31
°C
For convection and bar radiators rated up to 10A, 50Hz or 60Hz, 230VAC nameplate rating.

The *Heater Controller* can be built in two versions: with a thermopile sensor for accurate temperature control; or without, which allows you to vary the power over 15 different levels. The model shown here has the thermopile sensor so you can 'dial up' the temperature that you want.

voltage switching'). This minimises any generation of electromagnetic interference by the controller.

Two versions

As noted, this project can be built in one of two versions: with or without a thermopile sensor for temperature control. If you build it without the optional thermopile sensor, the knob on the front panel will allow you to vary the power over 15 different power levels.

The second version, with the thermopile sensor, provides a non-contact temperature measurement method by detecting the infrared radiation emitted by objects outside the box.

This form of room temperature sensing is ideal since the *Heater Controller's* circuitry runs at 230VAC mains potential, and any contact with an uninsulated external sensor would be dangerous.

By having the thermopile located safely inside the unit, with a transparent window for insulation, it is rendered safe and its operation is not affected by self-heating due to internal dissipation, as would be the case with an internal sensor.

The *Heater Controller* can be used with a 220-250VAC mains supply at 50Hz or 60Hz. However, It is ***not suitable*** for use with 110VAC supplies without some changes being made to the power supply and the mains voltage detection circuitry.

As you can see from the photos, the *Heater Controller* is mounted in a low-profile diecast aluminium case with mains plug and socket leads at one end, along with a fuse holder. The adjustment potentiometer is on the lid.

Circuit description

The complete circuit for the *Heater Controller* is shown in Fig.1. We'll start by describing the complete version, which provides temperature control.

The circuit is based around microcontroller IC1, Triac Q2 and thermopile sensor TS1.

IC1 provides overall control, driving the sensor and the Triac, which connects mains power to the heater.

TS1 has four pins and it actually comprises two separate devices in the one package. The thermopile IR sensor is connected between pins 2 and 3, while an NTC thermistor is connected between pins 1 and 4.

This is important because the thermopile senses the difference in temperature between the room and the sensor itself. The thermistor allows us to determine the sensor temperature. By adding the two temperatures, we can determine the absolute temperature of the room.

The microcontroller monitors several signals or voltages, which are internally converted to numbers using its inbuilt 10-bit analogue-to-digital converter (ADC).

The voltage across the NTC thermistor in TS1 is monitored by input AN3 (pin 3), while the voltage at the output from instrumentation amplifier IC2 is monitored at input AN0 (pin 7).

The setting of the control potentiometer (VR1) is monitored at input AN1 (pin 6) while the mains voltage is monitored at digital input GP2 (pin 5), via a 330kΩ 1W resistor.

IC1's GP5 output (pin 2) drives the base of NPN transistor Q1. In turn, Q1 sinks current from the gate of Triac Q2, switching it on. Its gate current flows via the 47Ω resistor connected between the 5.1V supply and the A1 terminal, through the gate and then to circuit ground via Q1.

This is a slightly unusual configuration. The gate resistor (in our case, 47Ω) is normally placed between the Triac gate and transistor collector, with the A1 terminal connected directly to the supply (in our case 5.1V). However, with that arrangement, noise on the mains Live conductor could be injected into the microcontroller supply and cause it to latch up.

In our circuit, the 47Ω resistor between the mains Live and 5.1V supply provides isolation to avoid this problem, while still limiting the gate current in exactly the same manner.

Q2's A1 terminal connects to the incoming mains Live supply via a 10A fuse. Q2 is used as a switch for making power connection from mains Live to the heater, via the A2 terminal.

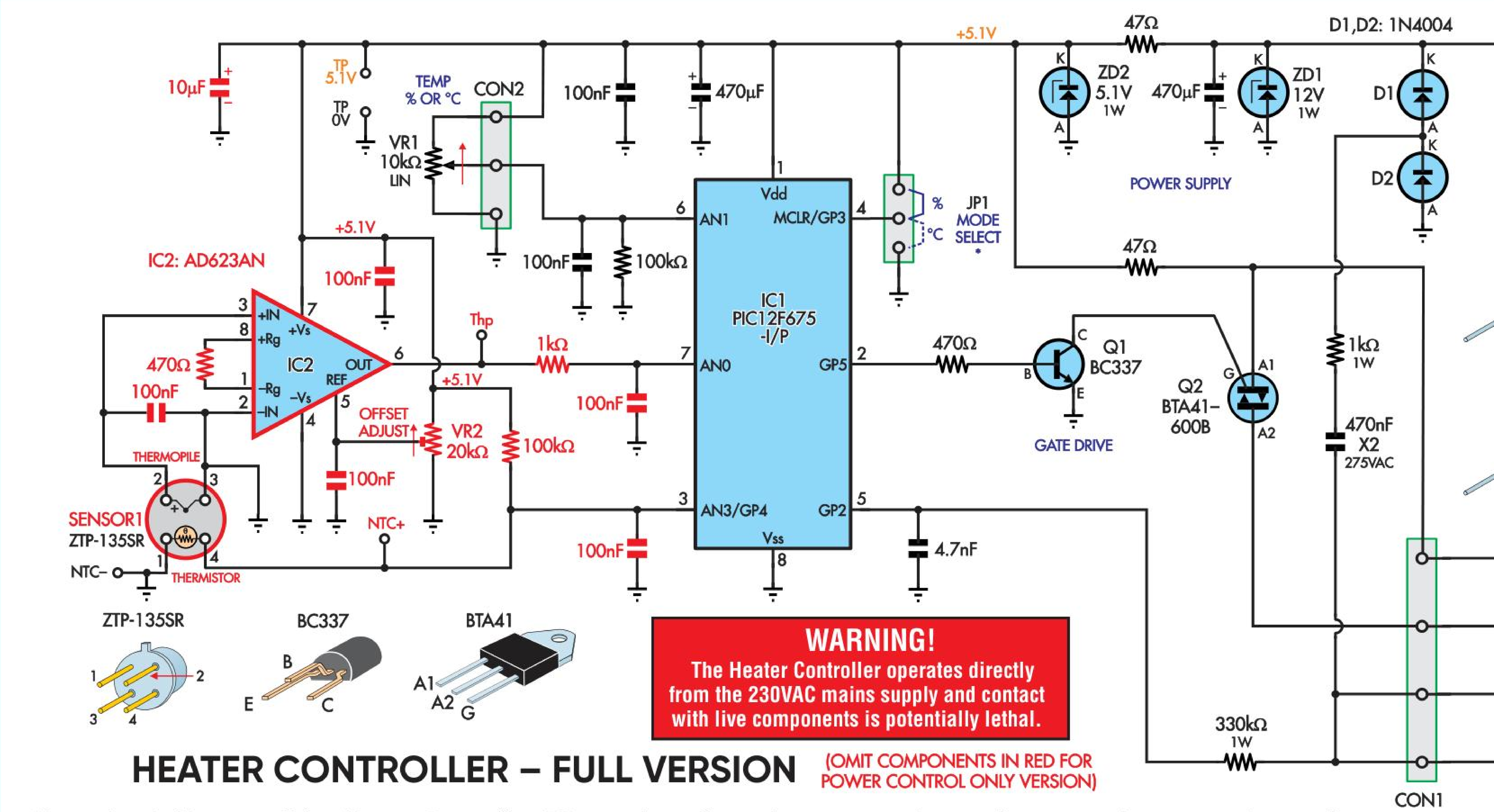
The DC supply for the microcontroller is derived directly from the 230VAC mains supply via a 470nF 275VAC X2-rated capacitor in series with a 1kΩ 1W resistor.

The capacitor's impedance limits the average current drawn from the mains, while the 1kΩ resistor limits the surge current when the power is first applied.

It works in the following way. When the Neutral line is positive with respect to the Live line, current flows via the 470nF capacitor and

Features and specifications

- ✓ Controls 230VAC heaters up to 10A/2300W.
- ✓ Suitable for use with bar heaters, ceramic heaters or oil-filled convection heaters. **Not suitable** for halogen or fan heaters.
- ✓ 220-250VAC mains operation, 50Hz or 60Hz.
- ✓ Heating power or temperature control
- ✓ Power control: 15 steps from low to full heating power. 300ms (50Hz) or 250ms (60Hz) cycle.
- ✓ Temperature control: 15–31°C in 1°C steps.
- ✓ Zero-voltage switching for low interference.
- ✓ Triac gate drive: 68mA pulse for 300µs after each zero-voltage crossing.


+5.1V
47Ω
D1,D2: 1N4004
10µF
TP 5.1V
TP 0V
TEMP % OR °C
CON2
100nF
470µF
K
ZD2 5.1V 1W
A
470µF
ZD1 12V 1W
D1
D2
VR1 10kΩ LIN
POWER SUPPLY
1
Vdd
6
AN1
MCLR/GP3
4
%
°C
JP1 MODE SELECT
+5.1V
IC2: AD623AN
100nF
100kΩ
47Ω
3
+IN
7
8
+Rg
+Vs
IC1 PIC12F675 -I/P
Thp
1kΩ
470Ω
C
Q1 BC337
1kΩ 1W
470Ω
IC2
OUT
6
7
AN0
2
GP5
B
E
Q2 BTA41-600B
G
A1
A2
1
REF
100nF
–Rg
+5.1V
100nF
2
–Vs
–IN
4
5
OFFSET ADJUST
VR2 20kΩ
100kΩ
GATE DRIVE
470nF X2 275VAC
THERMOPILE
2
3
100nF
SENSOR1
ZTP-135SR
NTC+
3
AN3/GP4
GP2
5
1
4
Vss
100nF
8
4.7nF
NTC–
THERMISTOR
ZTP-135SR
BC337
BTA41
1
2
3
4
B
E
C
A1
A2
G
330kΩ 1W
CON1

WARNING!
The Heater Controller operates directly from the 230VAC mains supply and contact with live components is potentially lethal.

HEATER CONTROLLER – FULL VERSION (OMIT COMPONENTS IN RED FOR POWER CONTROL ONLY VERSION)

Fig.1: circuit diagram of the *Heater Controller*. IC1 monitors the mains zero crossing at pin 5, potentiometer setting at pin 6, the internal temperature at pin 3 and external temperature difference at pin 7. It uses this information to decide when to deliver a gate pulse from pin 2, to switch on Triac Q2, which applies one cycle of mains power to the heater at a time.

diode D1 to the 470µF capacitor to charge it up. On negative half-cycles, the current through the 470nF capacitor is reversed via diode D2.

Zener diode ZD1 limits the voltage across the 470µF capacitor to 12V, and that supply then feeds a second 470µF capacitor via a 47Ω resistor and its voltage is limited to 5.1V by zener diode ZD2.

This is the supply for the microcontroller (IC1) and it is decoupled with a 100nF capacitor close to the micro.

IC1 monitors the GP3 digital input at pin 4 and this can be tied to the 5.1V supply or to 0V using a jumper shunt at JP1. When this pin is pulled high, the reading from VR1 is used to control the percentage of full power delivered to the heater.

When this pin is pulled low, the heater is temperature controlled instead, using TS1 for feedback.

VR1 is connected across the 5.1V supply with the wiper connected to the AN1 input, as described earlier. The 100kΩ resistor from the wiper to ground holds the AN1 input at 0V, setting the control to minimum, should VR1's wiper go open circuit.

Temperature measurement

The resistance of the thermistor in TS1 decreases with increasing temperature and therefore it has a negative temperature coefficient (NTC).

Its value at 25°C is close to 100kΩ and will be reduced at higher temperatures. Its resistance is monitored indirectly at the AN3 input of IC1, by connecting the thermistor as part of a voltage divider, ie, with a 100kΩ resistor to the 5.1V supply.

The resulting voltage is converted to a digital value in IC1 and that value is used to compute the sensor temperature in °C using a table that lists the expected voltage against temperature.

At 25°C, the thermistor's resistance of 100kΩ matches that of the fixed resistor, so the voltage between NTC– and NTC+ should be half of the 5.1V supply (ie, around 2.55V). The thermistor resistance changes in a non-linear manner with respect to temperature.

Here's an online calculator that can be used to determine how the thermistor resistance varies with temperature, by plugging in a Beta value of 3960 and a resistance at 25°C of 100kΩ: **http://bit.ly/pe-apr19-ntc**

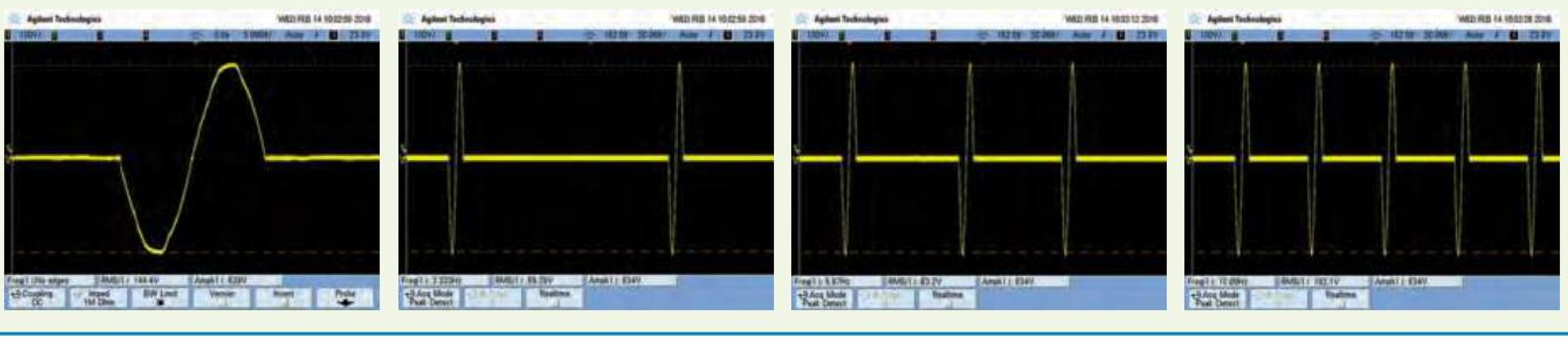
For example, we can determine that if the sensor is at 15°C, the thermistor resistance will be around 158556Ω, giving a voltage of 3.13V (5.1V x 158556Ω ÷ [158556Ω + 100kΩ]) across the thermistor (ie, at V_{out1}), assuming the supply voltage is exactly 5.1V.

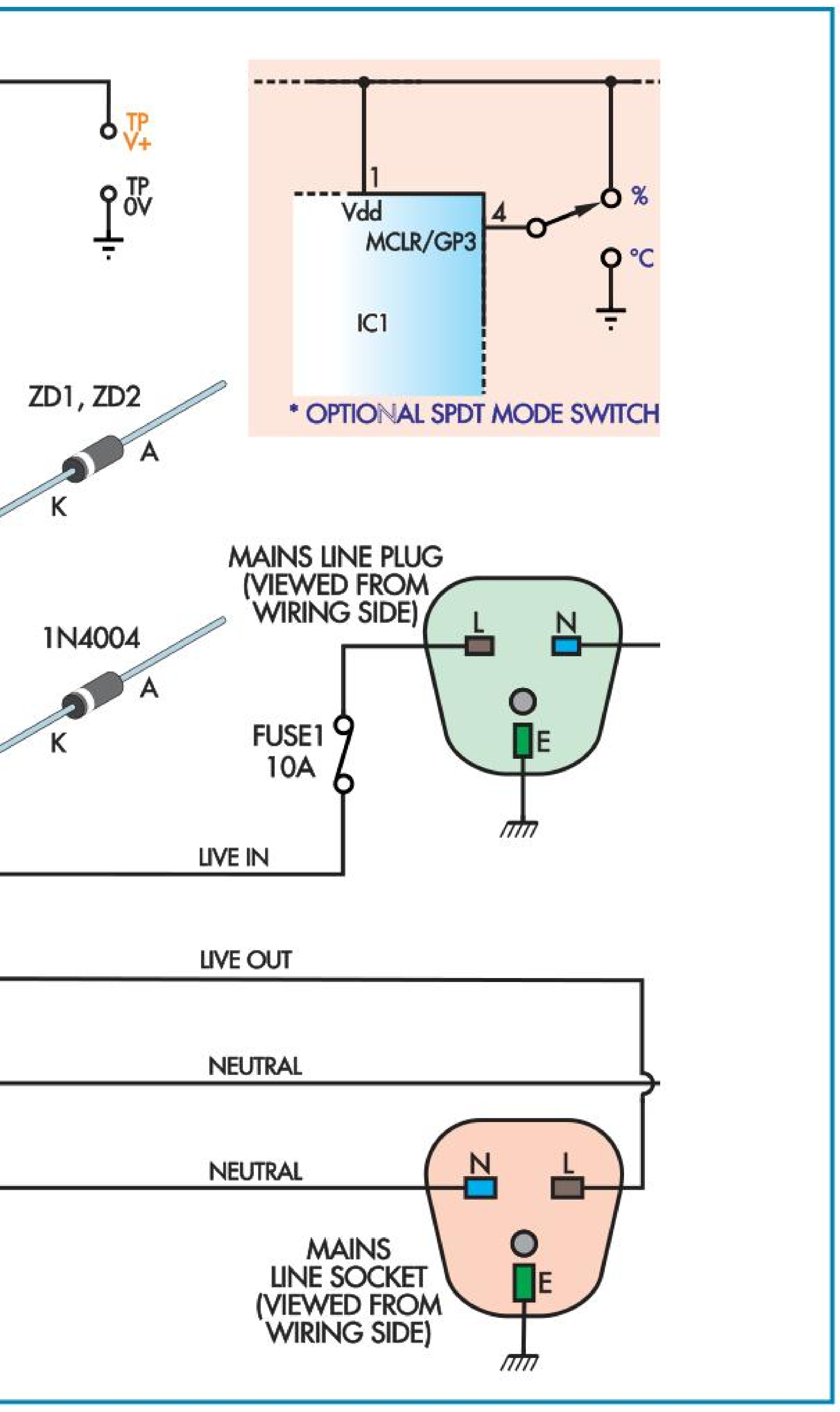
So that determines the temperature of the sensor itself. The thermopile output voltage allows us to determine the difference between the sensor temperature and the room temperature, but it is a very small voltage and needs amplification before it can be measured by IC1.

To achieve this, we use an instrumentation amplifier (IC2). The amplifier gain is set at about 211 by the value of resistor Rg, 470Ω. This amount of gain gives IC2's output a slope of 10mV/°C. (The gain takes into account the losses in infrared heat through the lens used to cover the sensor.)

The output voltage of IC2 is referenced against a non-zero voltage so that

The first in this series of scope grabs shows the zero-voltage switching action of the Triac. The remainder show how the number of cycles is increased to increase the power.




TP V+
TP 0V
1
Vdd
MCLR/GP3
4
%
°C
IC1
* OPTIONAL SPDT MODE SWITCH
ZD1, ZD2
A
K
MAINS LINE PLUG (VIEWED FROM WIRING SIDE)
L
N
E
1N4004
A
K
FUSE1 10A
LIVE IN
LIVE OUT
NEUTRAL
NEUTRAL
N
L
E
MAINS LINE SOCKET (VIEWED FROM WIRING SIDE)

we can measure the room temperature even if it is colder than sensor TS1.

So if the output from IC2 is at this reference voltage, the thermopile measurement is zero degrees (ie, ambient equals sensor temperature). The reference voltage is set by trimpot VR2 to half-supply – ie, 2.55V.

If the output of IC2 is 20mV above the reference voltage then the temperature difference is +2°C.

The micro adds this differential temperature to the sensor temperature, computed as explained above, to gauge the room temperature.

The negative end of the thermopile (pin 3 of TS1), which connects to the inverting input of IC2 (pin 2) is connected to ground.

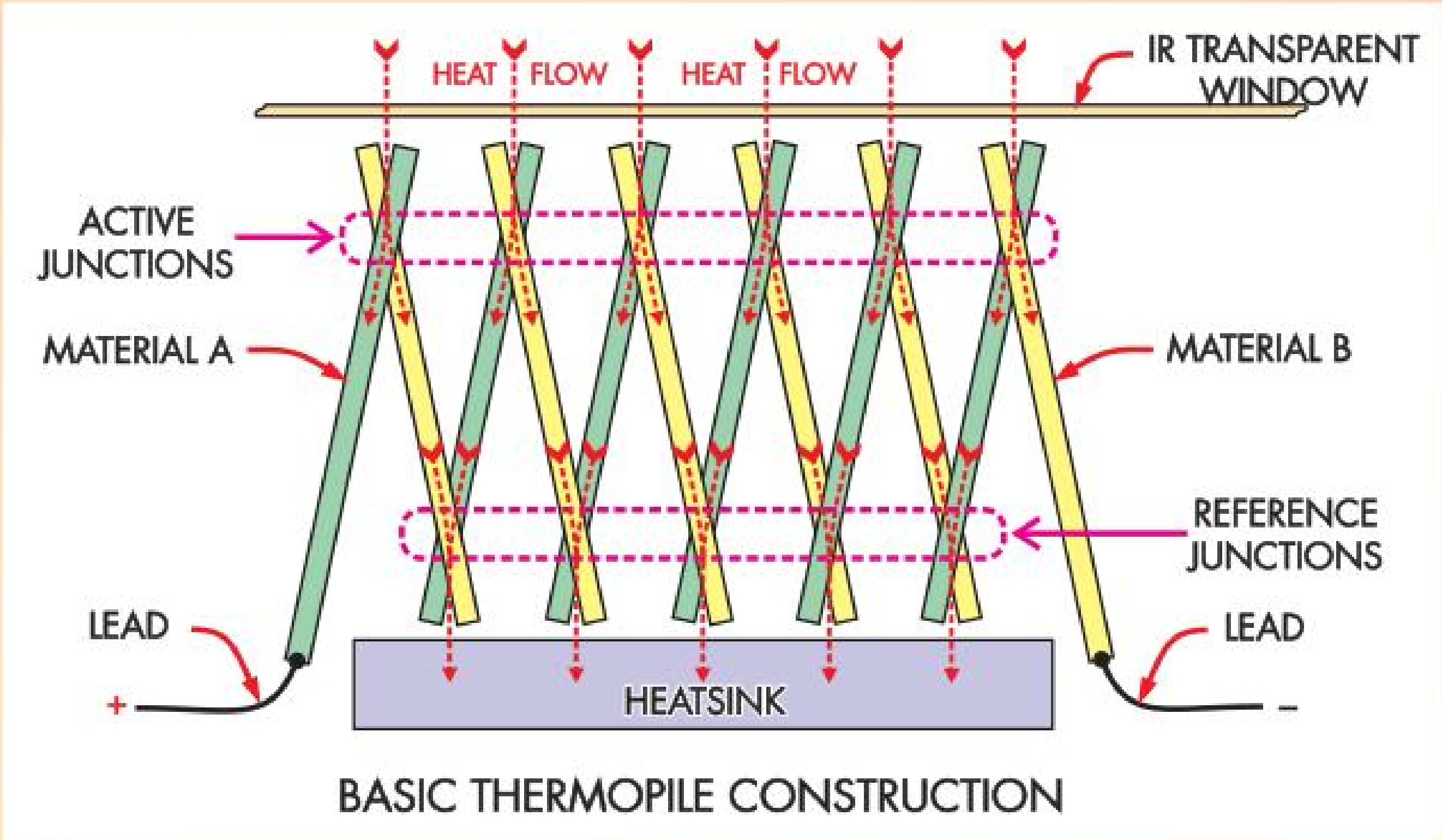
Thus, the positive output of the thermopile, at pin 2 of TS1, can vary above or below ground, depending on whether the outside temperature is above or below the sensor temperature.

The thermopile is a voltage source and it can generate a negative voltage, despite the circuit not having a negative supply.

However, instrumentation amplifier IC2 can handle input voltages down to 150mV below its negative supply. The thermopile output voltage is typically within ±1mV so this is not a problem.

The 100nF capacitors at the AN0, AN1 and AN3 inputs of IC1 provide a low-impedance source for the analogue-to-digital converter's sample-and-hold circuitry.

What is a thermopile?



BASIC THERMOPILE CONSTRUCTION

A thermopile is a 'pile' of thermocouples that are exposed to the outside via an infrared window. A thermocouple is a junction between two dissimilar conductors, bonded together as shown.

One set of junctions is exposed to infrared energy while the other set is shielded from the infrared and thermally connected to a reference thermal mass. This is indicated as a heatsink in the diagram.

The thermopile we are using has 60 thermocouples connected in series, so their voltages are added together.

The output voltage from the thermopile varies with the difference between the temperature of the infrared-exposed junctions and the heatsink-connected junctions. If the infrared radiation heats the first set of junctions up to the same temperature as the heatsink, then their output will be at 0V.

The output voltage can be positive or negative, depending on whether the heatsink connected junctions are colder (positive) or hotter (negative) than the infrared exposed junctions.

The fact that the temperature measurement is based on received infrared energy means that this is a non-contact method of temperature measurement. All objects which are above absolute zero give off some infrared energy and the hotter they are, the more they emit; hence we can use this energy as a way to remotely sense a body's temperature.

The sensor we are using also includes an NTC thermistor, which is joined to the heatsink. This allows the heatsink temperature to be measured. The temperature of the monitored object (ie, the source of infrared energy) is the heatsink temperature plus the temperature measured by the thermopile.

So if the thermopile package temperature is 25°C, as measured by the thermistor, and the thermopile infrared temperature measurement is registering 4°C, then the actual temperature measurement is 29°C (25°C + 4°C). If the thermopile registers –3°C then the result is 22°C (25°C – 3°C).

The thermopile includes an infrared-transparent window that allows the infrared energy into the thermopile. We are also using an external lens, to protect against accidental contact with the circuitry on the inside of the box.

One more thing to note about thermopiles: while we said above that the infrared emissions from an object depend on its temperature and that is true, they also depend on the colour of the object's surface.

A 'black body' is an ideal emitter, with an emissivity of 1.0 and the thermopile is calibrated to accurately measure the temperature of such objects. All other objects have an emissivity between zero and one and as a result, the thermopile will pick up less infrared energy at any given temperature and so will measure less than their actual temperature.

Examples of objects with low emissivity include most shiny objects, for example, with polished metal surfaces. To accurately measure the temperature of an object based on infrared energy, you need to know the emissivity and divide the measurement by this value.

In the case of our Heater Controller, the emissivity of a typical room should be high enough, and the difference between internal and external temperature low enough, that such compensation should not be necessary.

We do, however, suggest that you avoid pointing the IR window at very shiny or polished objects.

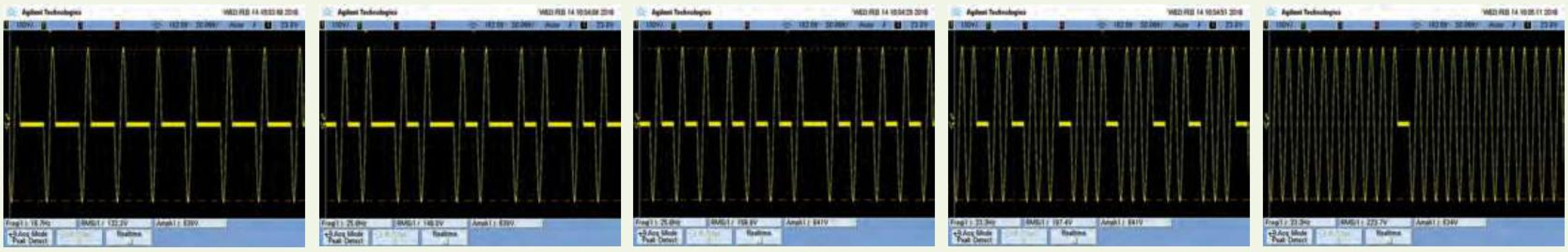
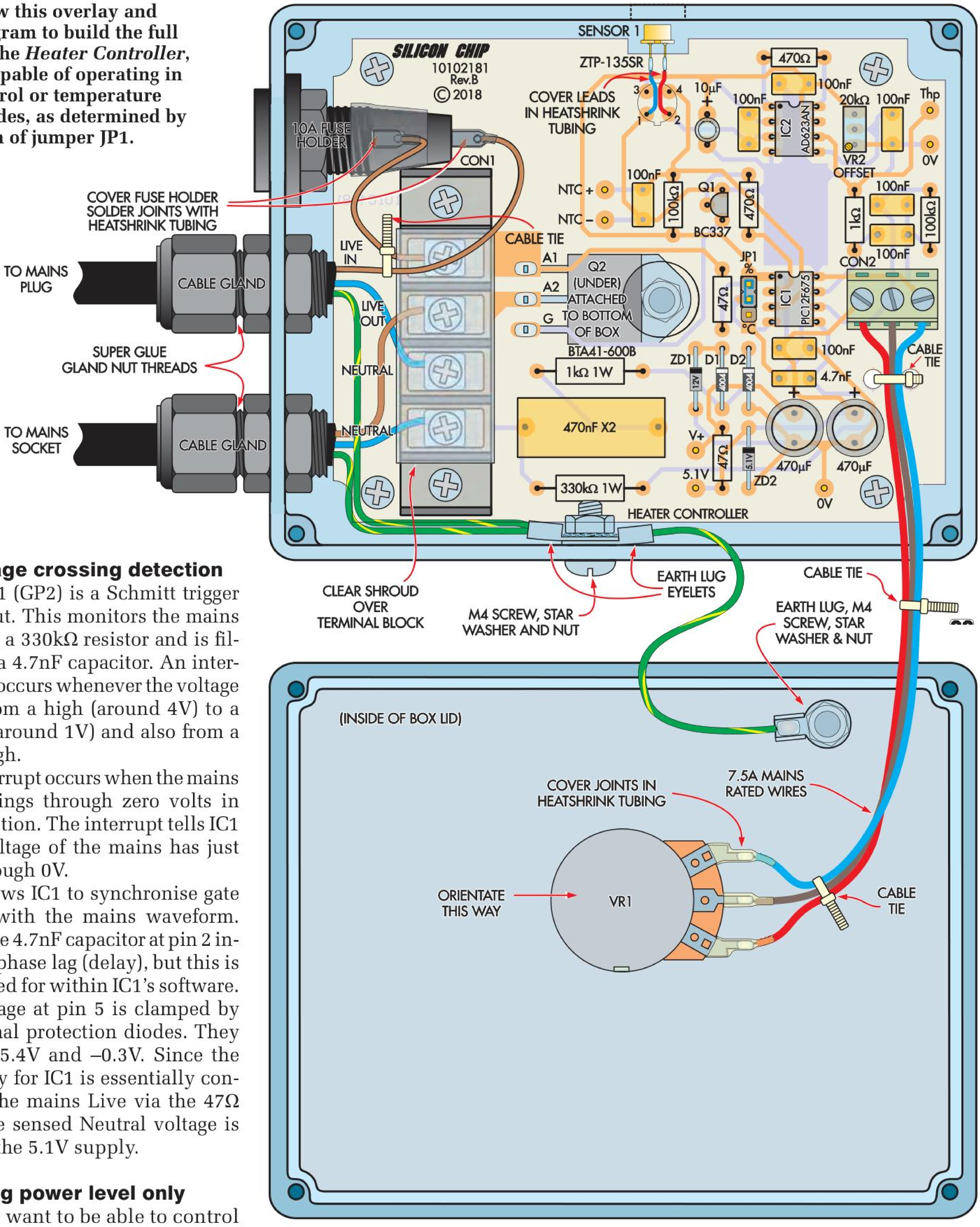


Fig.2: follow this overlay and wiring diagram to build the full version of the *Heater Controller*, which is capable of operating in power control or temperature control modes, as determined by the position of jumper JP1.


SENSOR 1
SILICON CHIP
10102181
Rev.B
© 2018
ZTP-135SR
COVER LEADS IN HEATSHRINK TUBING
3
4
1
2
10µF
470Ω
100nF
100nF
20kΩ
100nF
Thp
IC2
AD623AN
VR2 OFFSET
0V
10A FUSE HOLDER
CON1
COVER FUSE HOLDER SOLDER JOINTS WITH HEATSHRINK TUBING
NTC +
NTC –
100nF
100kΩ
Q1
BC337
470Ω
1kΩ
100nF
100kΩ
100nF
CON2
CABLE TIE
TO MAINS PLUG
CABLE GLAND
LIVE IN
A1
A2
G
Q2 (UNDER) ATTACHED TO BOTTOM OF BOX
BTA41-600B
JP1
%
°C
47Ω
IC1
PIC12F675
LIVE OUT
100nF
CABLE TIE
SUPER GLUE GLAND NUT THREADS
NEUTRAL
ZD1
D1
D2
12V
4004
4004
1kΩ 1W
4.7nF
TO MAINS SOCKET
CABLE GLAND
NEUTRAL
470nF X2
V+
47Ω
5.1V
ZD2
5.1V
470µF
470µF
0V
330kΩ 1W
HEATER CONTROLLER
CLEAR SHROUD OVER TERMINAL BLOCK
M4 SCREW, STAR WASHER AND NUT
EARTH LUG EYELETS
CABLE TIE
EARTH LUG, M4 SCREW, STAR WASHER & NUT
(INSIDE OF BOX LID)
COVER JOINTS IN HEATSHRINK TUBING
7.5A MAINS RATED WIRES
ORIENTATE THIS WAY
VR1
CABLE TIE

Zero voltage crossing detection

Pin 5 of IC1 (GP2) is a Schmitt trigger digital input. This monitors the mains Neutral via a 330kΩ resistor and is filtered with a 4.7nF capacitor. An interrupt in IC1 occurs whenever the voltage changes from a high (around 4V) to a low level (around 1V) and also from a low to a high.

That interrupt occurs when the mains voltage swings through zero volts in either direction. The interrupt tells IC1 that the voltage of the mains has just passed through 0V.

This allows IC1 to synchronise gate triggering with the mains waveform. Note that the 4.7nF capacitor at pin 2 introduces a phase lag (delay), but this is compensated for within IC1's software.

The voltage at pin 5 is clamped by IC1's internal protection diodes. They clamp at +5.4V and –0.3V. Since the 5.1V supply for IC1 is essentially connected to the mains Live via the 47Ω resistor, the sensed Neutral voltage is relative to the 5.1V supply.

Controlling power level only

If you only want to be able to control the heater power and don't need temperature regulation, jumper JP1 is set to pull pin 4 of IC1 high. In this case, there is no need to install TS1 or IC2, trimpot VR2, nor any of the associated resistors and capacitors (see Fig.3). This would reduce the cost of building the unit.

Note that it would be possible to build the unit so that it could be used in either mode, by fitting a 250VAC-rated single-pole double-throw toggle switch to the box and wiring it in place of JP1. In percentage control mode, the temperature sensed by TS1 would be ignored.

Construction

The *Heater Controller* is built on a double-sided, plated-through PCB (printed circuit board) coded 10102181 and measuring 103 x 81mm. This is mounted inside a diecast box of 119 x 94 x 34mm.

Fig.2 above shows where the components are fitted for the full version of the *Heater Controller* – which can regulate the temperature. Fig.3 on the opposite page shows the components fitted which are required for just controlling the heater power level (percentage).

Follow the overlay diagram appropriate to your version. Start by installing the resistors – you should also check each resistor using your DMM (digital multimeter).

Three additional wire links are fitted for the heater-power-control-only version. These are shown in Fig.3; one to set the mode, in place of JP1, and two to hold the AN0 and AN3 inputs of IC1 at 0V. Use resistor lead off-cuts to make these links now.

Following this, install the diodes, which must be oriented as shown. Note that there are several different diode

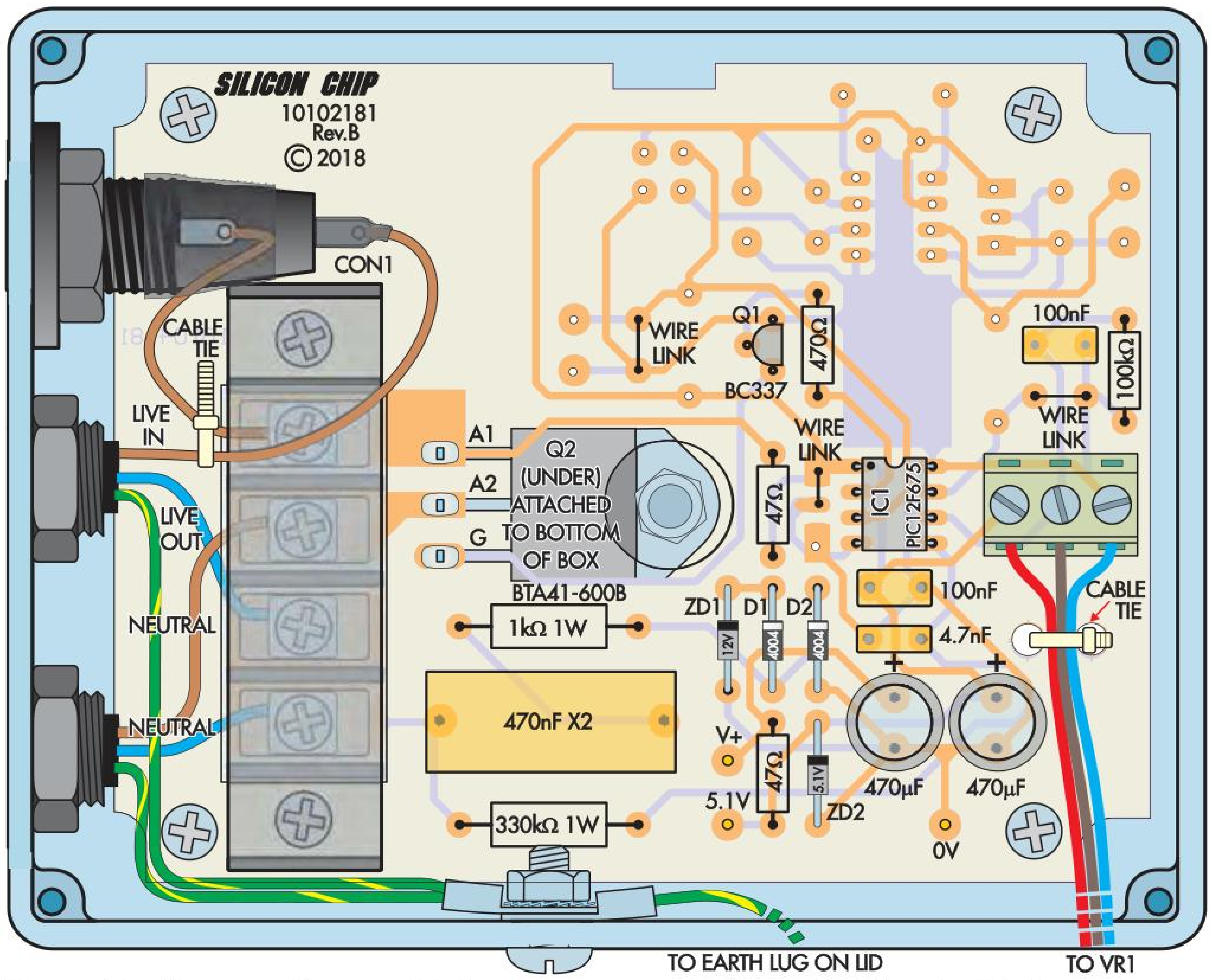
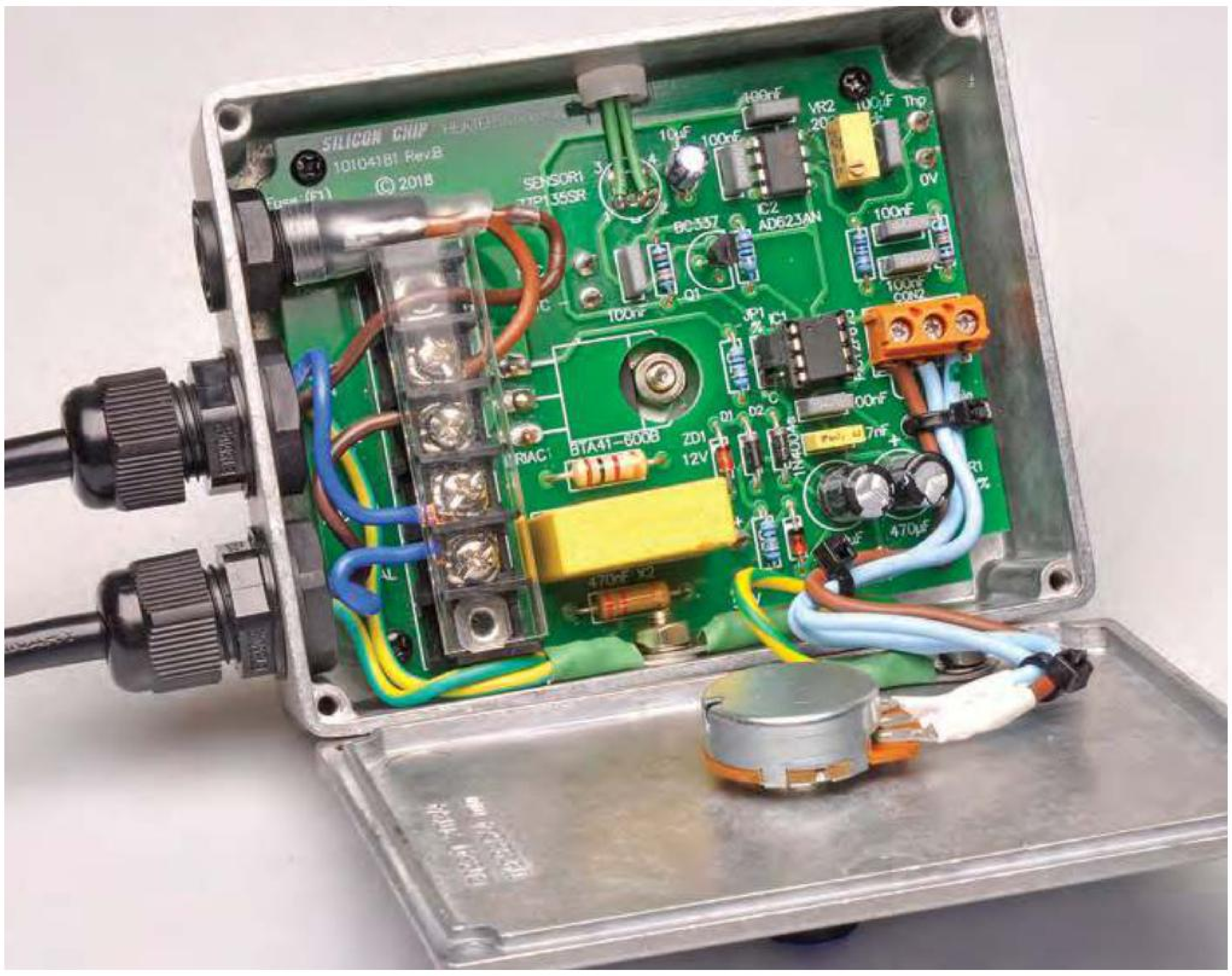


Fig.3: this diagram shows which components can be omitted, to build the unit only for heater power control. JP1 is replaced with a wire link and two additional wire links are fitted where shown. The photo below is of the full version and shows all wiring completed and secured, as in the diagram opposite.



types: standard 1N4004 diodes for D1 and D2; a 12V 1W zener (1N4742) for ZD1; and a 5.1V 1W zener (1N4733) for ZD2.

IC1 is mounted on an 8-pin DIL socket, so install its socket now, taking care to orient it correctly. Leave IC1 out for the time being, though. IC2 is installed for the full version, soldered directly on the PCB. Transistor Q1 can also be installed now.

Fit the capacitors next. The X2 class capacitors and the polyester types are usually printed with a code to indicate their value

The electrolytic types are marked with their µF (microfarad) value and must be oriented with the polarity shown. The longer lead is positive and the negative end is usually marked on the can with a stripe.

The screw terminals and trimpot can be installed now. The 3-way terminal block for CON2 is fitted with the lead entry toward the lower edge of the PCB. VR2 has its adjustment screw near the top edge of the board, as shown in Figs.2 and 3. If you are fitting a pin header for JP1, then solder this in place now.

TS1 is fitted for the full version and is mounted along the edge of the board. This arrangement is shown in Fig.4. The sensor is located centrally within the cut-out on the side of the board, with the leads to pins 1 and 2 along the top of the PCB and the leads to pins 3 and 4 along the underside.

You can either use PC stakes to connect the lead of TS1 to the PCB terminals, or bend the sensor leads to fit into the PCB holes directly. Make sure the leads for pins 1 and 2 do not short to the pads on the PCB for pins 3 and 4; a small piece of electrical tape or heathsrink tubing could be used to insulate them from the board.

Any pigtails on the underside of the PCB, including the ends of PC stakes, must be cut short to prevent contact with the base of the sensor. Leave Triac Q2 to be installed later.

Preparing the case

Now you need to drill some holes in the diecast enclosure. Drilling templates are provided in Fig.5 and can be downloaded from the *PE*/*EPE* website. The lid requires a 9.5mm-diameter hole for potentiometer VR1 and a 4mm Earth screw hole, so drill them now.

If building the full version, follow the instructions below. Otherwise, go to the heading titled 'PCB location'.

The first hole to be drilled in the box base is for the lens. This is on the side of the box and is 9mm in diameter.

Once drilled, fit the lens into the hole with the two protruding locating prongs on the rear rim of the lens housing, both facing downward. Attach three of the four 8mm spacers to the PCB with the screws from the top of the PCB. The omitted spacer can be the one nearest VR2 or near fuse F1.

Now place the PCB into the box with the thermopile sensor entering the lens. While holding the PCB in place, press the PCB toward the lens so that it is held tightly in place.

Align the PCB so it is squarely positioned in the box and mark the mounting hole position for the missing spacer on the base of the box, then drill this hole to 3mm and check that the hole is correctly positioned.

If adjustment is needed, file the hole with a small needle file so it is correctly positioned. Once correct, remove the spacers and lens, and place the PCB in the box. Align it with the hole already drilled. When the PCB is squarely positioned, mark out and drill the remaining three holes.

PCB location

Note that when the PCB is in the box, the CON1 screw terminal end of the PCB sits further away from the end of

Parts list – Heater Controller

- 1 double-sided PCB coded 10104181, 103 x 81mm
- 1 diecast aluminium box 119 x 94 x 34mm [Jaycar HB-5067]
- 1 Fresnel lens for IR sensor (Murata IML0688) [RS components Cat 124-5980] †
- 1 M205 10A safety panel-mount fuse holder with 10A M205 fuse (F1) [Altronics S5992]
- 1 4-way PC mount terminal barrier (CON1) [Jaycar HM-3162]
- 1 3-way PC-mount terminal block with 5.08mm pin spacings (CON2)
- 2 cable glands for 5-10mm cable
- 1 DIL-8 IC socket
- 1 3-pin header with 2.54mm spacing and shorting block †
- 1 2m-long 10A mains extension lead
- 1 knob to suit VR1
- 4 4mm eyelet connectors
- 4 8mm-long M3 tapped nylon spacers
- 3 M4 x 10mm screws
- 2 4mm ID star washers
- 3 M4 hex nuts
- 8 M3 x 5mm machine screws
- 4 stick-on rubber feet
- 10 PC stakes †
- 1 100mm length of 3mm-diameter heatshrink tubing
- 1 25mm length of 6mm-diameter green heatshrink tubing, if required for eyelet lugs
- 3 100mm lengths of 250VAC 7.5A mains wire (for VR1)
- 4 100mm long cable ties

Semiconductors

- 1 PIC12F675-I/P microcontroller programmed with 1010418A.hex (IC1)
- 1 AD623AN instrumentation amplifier (IC2) †
- 1 ZTP135SR thermopile sensor (TS1)‡ [element14 Cat 2506255]
- 1 BTA41-600BRG insulated tab 40A 600V Triac (Q2) [element14 Cat 1057288, RS Components Cat 687-1007]
- 1 BC337 NPN transistor (Q1)
- 1 12V 1W (1N4742) zener diode (ZD1)
- 1 5.1V 1W (1N4733) zener diode (ZD2)
- 2 1N4004 1A diodes (D1,D2)
- Super glue, heatsink compound, solder

Capacitors

- 2 470μF 16V PC electrolytic
- 1 10μF 16V PC electrolytic †
- 1 470nF 275VAC X2 class
- 7 100nF 63V or 100V MKT polyester ‡
- 1 4.7nF 63V or 100V MKT polyester

Resistors (0.25W, 1%)

- 1 330kΩ 1W
- 1 1kΩ 1W
- 2 100kΩ §
- 2 470Ω §
- 1 1kΩ †
- 2 47Ω

- 1 20kΩ multi-turn top adjust trimpot (code 203, 3296W style) (VR2)†
- 1 10kΩ linear 24mm potentiometer (VR1)

(† not required for power control only version)

(§ 1 required for power control only version)

(‡ 2 required for power control only version)

the box compared to the other end. This allows space for the cable gland nuts. Holes for the fuse, cable glands and Earth screw can also be drilled now, making sure these are drilled at the CON1 end of the box.

Re-attach the 8mm-long spacers to the PCB. Then bend the Triac leads up at 90°, 4mm from the body of the Triac. Insert the leads into the PCB from the underside.

The PCB can now be secured to the case with the screws from the underside into the tapped spacers. Mark out the Triac mounting-hole position on the base of the case. Remove the PCB again and drill to 4mm. Clean away any metal swarf and slightly chamfer the hole edge.

Re-attach the PCB and adjust the Triac lead height so the metal tab sits flush onto the flat surface, then secure the Triac with the M4 screw and nut. Note that the metal tab is internally isolated from the leads and so does not require any further insulation between its tab and case. Solder the Triac leads at the top of the PCB, then trim them short.

Now remove the screws to gain access to the underside of the PCB and solder the Triac leads from the underside. The four stick-on rubber feet can now be attached to the base of the case now.

The case lid should be fitted with a panel label. We have designed three labels. One is for the power-control-only version, one is for a temperature-control-only version and the third option is for when JP1 can be used to select either control mode. These label files can be downloaded from the *PE/EPE* website.

Once the label has been attached, cut out the potentiometer hole and Earth screw hole with a hobby knife.

Wiring

Cut the 10A extension lead in two, to provide one lead with a plug on the end and another with a socket. Where the lead is cut depends on how long you prefer each lead.

You may prefer a long plug cord and short socket lead, so the heater is located near to the controller. Alternatively, the lead can be cut into two equal lengths. Before cutting though, make sure you have sufficient length to strip back the insulation, as detailed in the next two paragraphs.

Now strip back the outer insulation sheath by about 200mm on the socket lead so you can get a suitable 100mm length of Earth wire (green/yellow stripe) for the connection between the chassis and lid.

Then cut the blue Neutral wire and brown Live wires to 50mm. Some of the spare 150mm brown wire length can be used later to connect from the fuse to CON1.

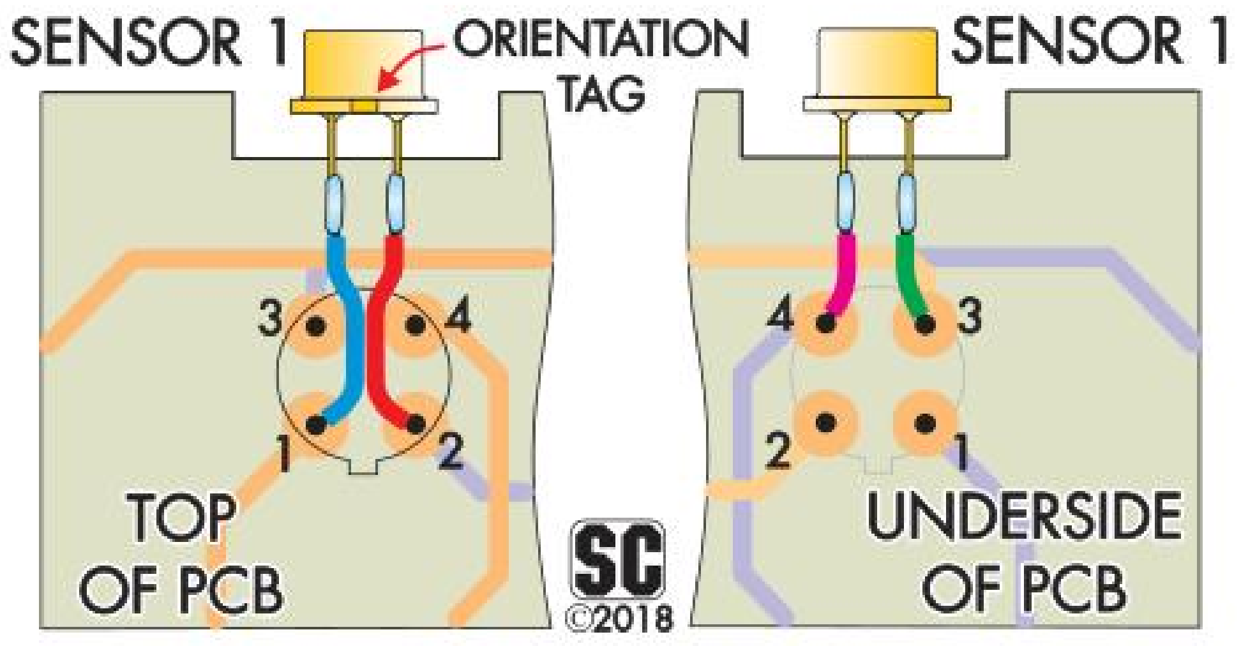
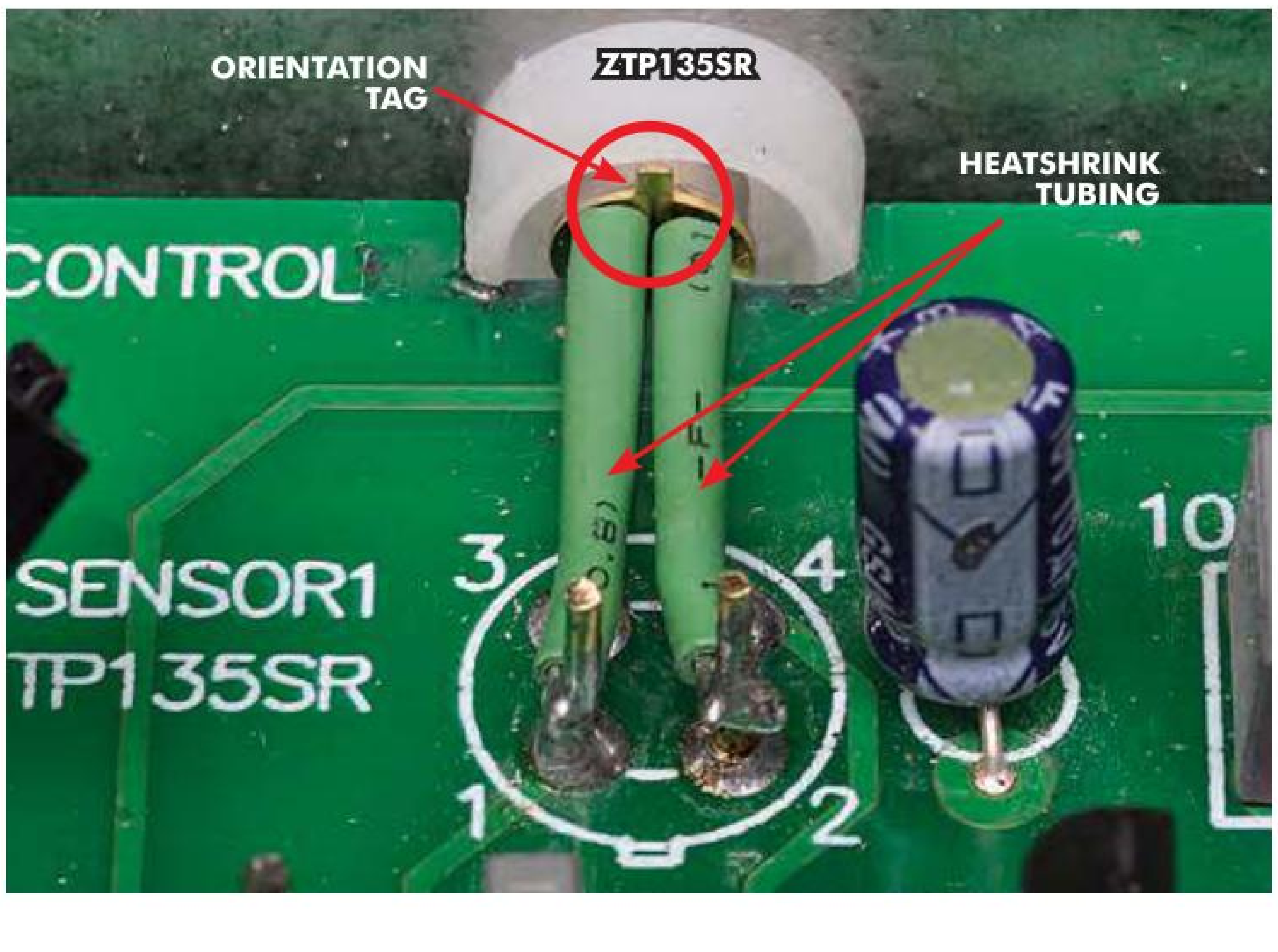


Fig.4: this diagram and the photos at right and below show how the sensor is mounted, with its lens emerging through an 11mm hole drilled through the side of the case.



SILICON CHIP
Heater Controller
10A Fuse

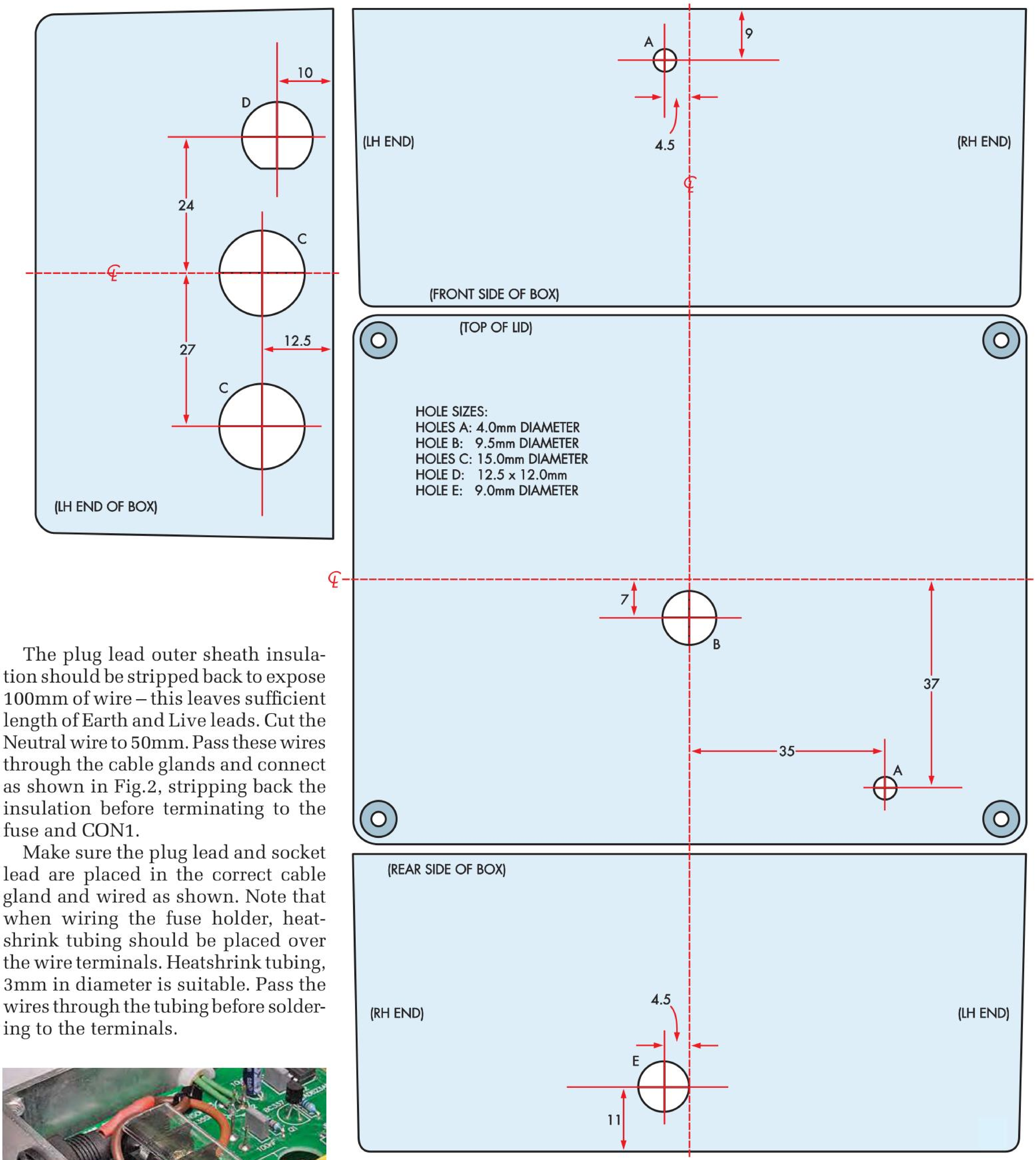
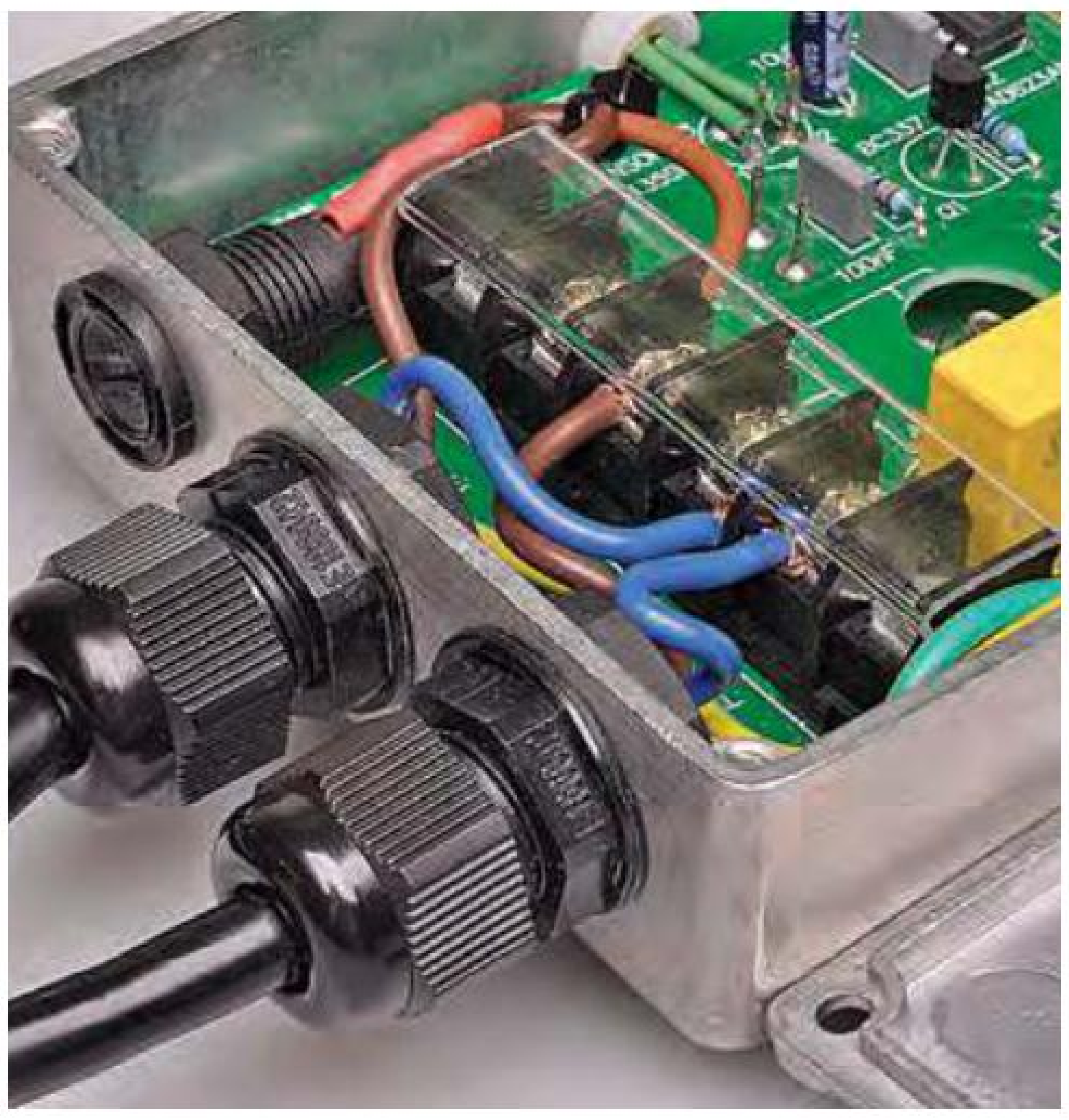

D
10
24
C
12.5
27
C
(LH END OF BOX)
℄
A
9
4.5
(LH END)
(RH END)
(FRONT SIDE OF BOX)
(TOP OF LID)
HOLE SIZES:
HOLES A: 4.0mm DIAMETER
HOLE B: 9.5mm DIAMETER
HOLES C: 15.0mm DIAMETER
HOLE D: 12.5 x 12.0mm
HOLE E: 9.0mm DIAMETER
7
B
37
35
A
(REAR SIDE OF BOX)
(RH END)
(LH END)
4.5
E
11

Fig.5: drilling and cutting templates for the diecast aluminium box and lid. The 'D'-shaped fuseholder hole should be drilled to 11mm and then filed to the shape shown here, to prevent the fuseholder from rotating. This drilling guide can be downloaded from the *PE/EPE* website.

The plug lead outer sheath insulation should be stripped back to expose 100mm of wire – this leaves sufficient length of Earth and Live leads. Cut the Neutral wire to 50mm. Pass these wires through the cable glands and connect as shown in Fig.2, stripping back the insulation before terminating to the fuse and CON1.

Make sure the plug lead and socket lead are placed in the correct cable gland and wired as shown. Note that when wiring the fuse holder, heatshrink tubing should be placed over the wire terminals. Heatshrink tubing, 3mm in diameter is suitable. Pass the wires through the tubing before soldering to the terminals.



Close-up view of the mains input and output section of the *Heater Controller*. Don't forget to place the protective shroud over the mains terminal block.

Cut the shaft of VR1 to 12mm long and file the edges smooth. Then attach the three 100mm lengths of 7.5A mains-rated wire to its three terminals and cover with 3mm heatshrink tubing. The other ends connect to CON2. These wires are held in place using a cable tie that feeds through holes in the PCB.

Attach VR1 to the lid and note that the potentiometer must be oriented as shown, so it fits beside the mains-rated capacitor on the PCB. Fit the knob; you may need to lift out the knob cap with a hobby knife and re-orient the cap so its pointer position matches the rotation marks on the panel. Apply a smear of heatsink compound to the underside of the Triac before installing the PCB inside the case.

Connect the Earth wires to M4 crimp or solder eyelets and cover with green

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heatshrink tubing. The eyelets attach to the side of the case and the lid using an M4 screw, star washer and nut.

IC1 can now be plugged in, taking care it is oriented correctly. Insert the 10A fuse into its holder. Press the cover onto the terminal barrier (CON1) to prevent accidental contact.

Check your construction carefully and especially check that the Earth wires (green/yellow striped) actually are connected to the case and Earth pins on the mains plug and socket. Check this with a multimeter set to read low ohms. The cable glands need to be tightened to hold the mains cords in place.

Because these are easily undone, the thread of the glands should have a drop of super glue (cyanoacrylate) applied to the threads before tightening. This way, the glands cannot be easily undone. Attach the lid using the four screws supplied with the case.

If you fitted the pin header for JP1, now plug the shorting block into the percentage (%) position. Connect a heater to the controller and with the lid in place, apply power and check that the power can be varied using VR1.

The following text only applies to the temperature-control version, so if you built this, unplug the unit, open up the lid and shift the shorting block into the alternative position.

Setting up the thermopile

The reference voltage needs to be adjusted now, and this procedure also compensates for any offset voltages present in TS1 and IC2.

Do not plug the unit into the mains directly during this procedure! You will need a supply that is between 5V and 9V DC, (eg, a 9V battery) connected between the 0V PC stake and the V+ PC stake on the PCB.

Monitor the thermopile voltage using a multimeter connected to the 0V (black) and Thp (red) terminals, then adjust VR2 so that the voltage at Thp is half the voltage measured at the terminal that's labelled 5.1V. So for example, if the supply is 5.1V, Thp should be set to 2.55V.

This adjustment must be done when the thermopile is measuring the same temperature as its own body. To ensure this, place a matte black object larger than the diameter of the lens directly in front of it.

This object needs to be the same temperature as the sensor, so place it nearby and leave it for an hour or so, to ensure that they are very close in temperature.

This 'black body' can be a block of wood painted *matte* black, the side of a black plugpack, a piece of matte acrylic or a black-handled kitchen utensil.

Final calibration

Final calibration is done with the unit powered from the mains, so make sure the lid is in place.

First, measure the ambient temperature with a thermometer and set VR1 to that setting, noting that calibration can only be done if the ambient temperature is within the range of 15-31°C. Switch on the power, and after about five seconds, check if the load is on or off. An incandescent lamp makes a suitable load (and you can see if it's on!).

Calibration is made by adjusting VR2, but this adjustment must be done only after power is switched off. So the adjustment will be a trial-and-error procedure.

VR2 needs to be adjusted clockwise if the load does not switch off when VR1 is set to just under ambient temperature. Adjust VR2 anticlockwise if the load is still off, with VR1 set to ambient temperature.

During this procedure, ensure that the lens is not blocked and has a good view of the room and is not pointed at a large window, oven, fridge, air conditioner or another source of heat/cold.

Temperature control mode

When using the *Heater Controller* as a thermostat, the thermopile will need to be placed so that the room temperature can be monitored.

This room temperature is best detected by using a non-shiny black object placed near the thermopile lens. The object should absorb the surrounding heat from the room air, allowing the thermopile to take the temperature reading.

In practice, you may just need to place the controller box and lens near to any object of any colour to have satisfactory temperature control.

The acceptance angle to the thermopile via the lens is about 84°. This can be visualised as a cone projecting out from the lens with an 84° angle at the base. This is close enough to 90° that 100mm from the lens, the area that is observed by the thermopile is a circle of 200mm diameter. In other words, it is a 1:2 ratio of the distance from the lens to the spot size.

Take care not to have the thermopile facing the heater itself. The high infrared level from the heater will cause the controller to switch off the heater. Bar radiator elements can reach 380°C, while convection heaters will be significantly above ambient.

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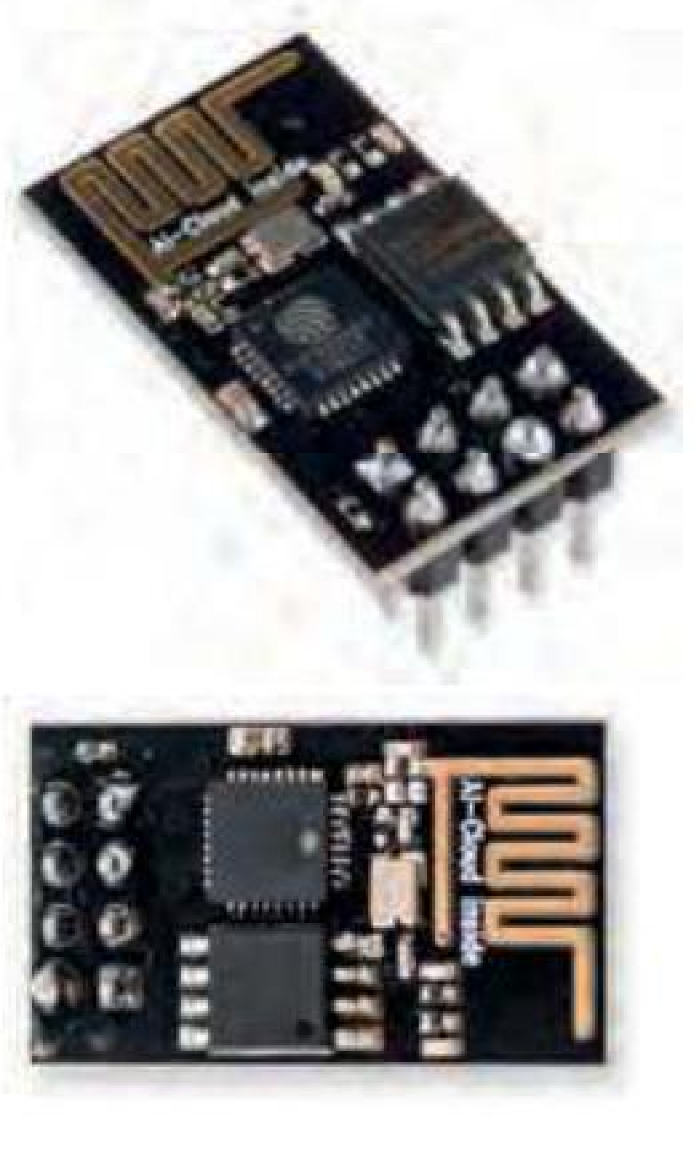
Using Cheap Asian Electronic Modules Part 15: by Jim Rowe

The ESP-01 Wi-Fi Data Transceiver



The ESP-01 is a very popular Wi-Fi transceiver module based on the ESP8266 IC, which is designed to allow almost any microcontroller to connect to a Wi-Fi network. To make this as easy as possible, the chip is programmed to respond to Hayes AT modem text commands. That's not all – the chip can be re-programmed to perform a variety of different tasks.

Wi-Fi networking has been around now for 20 years, after being adopted as a standard protocol in 1999 – the same year the Wi-Fi Alliance was formed. Since then, it has grown steadily in popularity, especially in mobile devices. It's also quite handy for wirelessly connecting computers to routers/modems and peripherals like printers.

Responding to this growth in Wi-Fi popularity, in mid-2013, Chinese semiconductor manufacturer Espressif Systems (based in Shanghai) released its ESP8266 chip. This is a complete SOC (system on a chip), combining a 32-bit RISC (reduced instruction set computer) microcontroller with a full TCP/IP (internet protocol) stack and all of the components needed for a Wi-Fi data transceiver.

But the ESP8266 didn't really make an impression in the Western world until 2014, when another Chinese firm, AI-Thinker, released its ESP-01 Wi-Fi transceiver module. This was based on the ESP8266, but what made it particularly popular was its cost at less than $4.00.

So the ESP-01 module and the ESP8266 chip are not new; they've been around for over three years, and we've used them in the *Internet-based 'GPS' Time Source* project – published in this issue on page 14.

That project actually features different modules based around the ESP8266 chip; there are dozens of different boards, many of them designed to be compatible with the Arduino system. Most of the information in this article regarding the ESP-01 applies equally to those other ESP8266-based modules.

We are taking a closer look at the ESP-01 module and ESP8266 chip here since they have numerous Wi-Fi and 'Internet of Things' (IoT) applications.

As an aside, Espressif has recently released a follow-up to the ESP8266 chip: the ESP32 series, which incorporate Wi-Fi and dual-mode Bluetooth transceivers and dual-core micros.

Although modules using the ESP32 chips have started to appear, their prices are significantly higher than that of the ESP-01 at around $9.00. But the ESP-01 still has some other advantages, such as lower power consumption in some situations. This has renewed interest in the ESP-01, especially since it's the easiest way to get started with Wi-Fi at the lowest cost.

About Wi-Fi

Wi-Fi is a technology for wireless local area networking, with devices complying with the IEEE 802.11 protocol standards. A large part of this is based on a patent (US5487069) developed at the CSIRO in Australia, by a team led by radio astronomer Dr John O'Sullivan.

The IEEE 802.11 protocol was first released in 1997 and has since been revised and updated numerous times. 802.11 is a set of MAC (media access control) and PHY (physical layer) specifications for implementing WLAN (wireless local area network) data communication in the 2.4GHz, 3.6GHz, 5GHz, 5.9GHz and 60GHz frequency bands.

There are many different versions of the 802.11 protocol. Those that are most popular for Wi-Fi are 802.11a, 802.11b/g/n and 802.11ac. These mainly differ in terms of their PHY specifications, as shown in Table 1.

The ESP8266 chip

The ESP8266 is a self-contained Wi-Fi networking transceiver and microprocessor, packaged in a single 32-pin QFN SMD chip measuring only 5 x 5mm. It operates in the internationally unlicensed 2.4-2.5GHz

Table 1: IEEE 802.11 Network PHY Standards commonly used for WiFi

Protocol	Frequency (GHz)	Bandwidth (MHz)	Stream data rate (Mbit/s)	Modulation	Approximate range (m)
802.11b	2.4 – 2.5	22	1, 2, 5.5, 11	DSSS	35 indoors, 140 outdoors
802.11g	2.4 – 2.5	20	6, 9, 12, 18, 24, 36, 48, 54	OFDM	38 indoors, 140 outdoors
802.11n	2.4/5.25–5.35	20/40	6.5–65/13.5–135*	MIMO-OFDM	70 indoors, 250 outdoors
802.11a	5/3.7 (USA)	20	1,2	OFDM	35 indoors, 120 outdoors
802.11ac	5.25–5.35	20/40/80/160	6.5–86.7/58.5–780*	MIMO-OFDM	35 indoors
802.11ad	60	2,160	Up to 6.75 Gbit/s	OFDM	60 indoors, 100 outdoors

DSSS: Direct Sequence Spread Spectrum OFDM: Orthogonal Frequency Division Modulation
MIMO-OFDM: Multiple Input, Multiple Output antennas with OFDM * Figures using a guard interval (GI) of 800ns

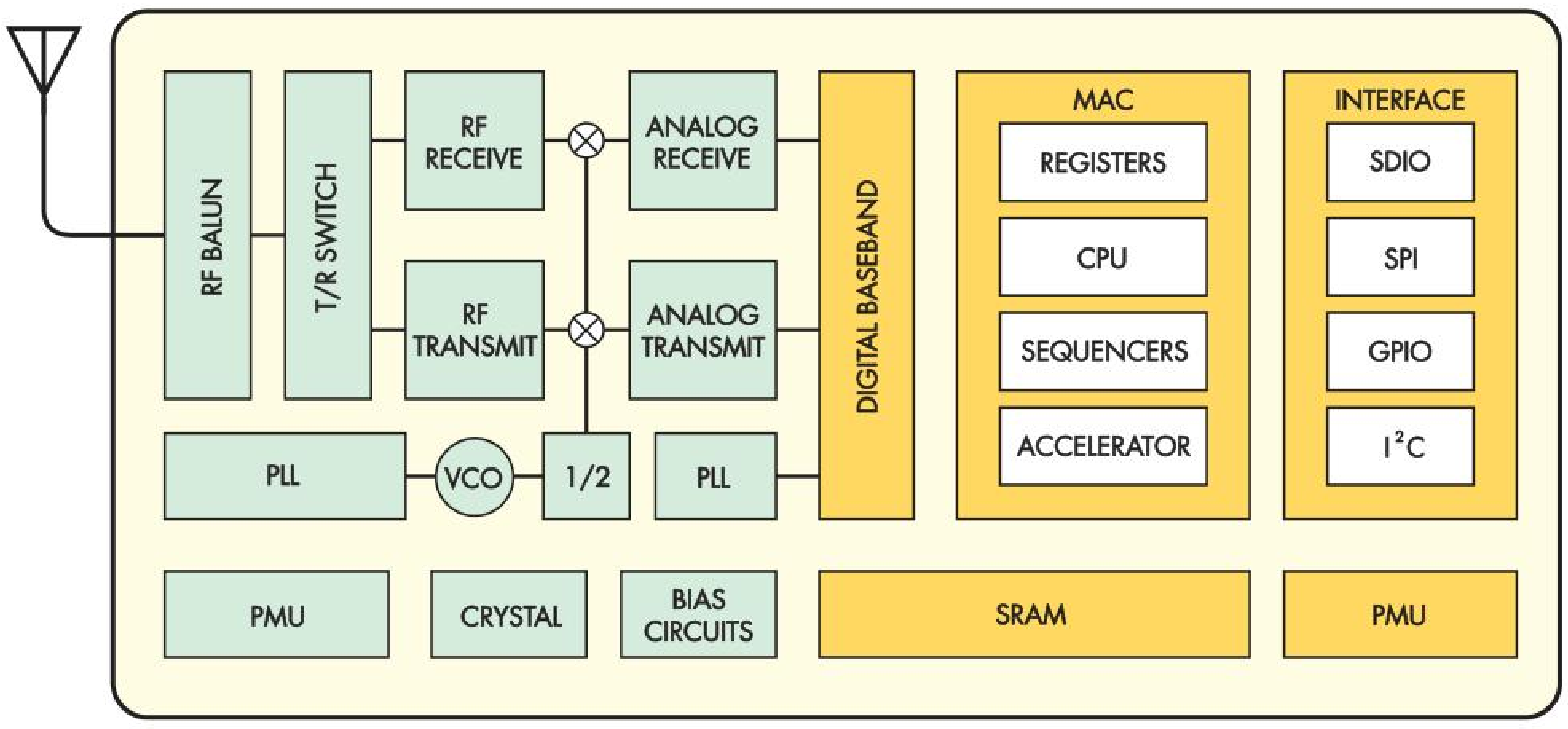


Fig.1: block diagram of the ESP8266 IC. The left-hand side of the diagram contains the RF sections, while the right-hand side is the baseband and CPU section.

ISM (Industrial, Scientific and Medical) band and is compatible with the 802.11b/g/n protocols.

The downside to the 2.4-2.5GHz band is that it is also used by Bluetooth devices, microwave data transceivers using the Nordic nRF24L01+ chip and is also plagued with various sources of noise like microwave ovens. So this is a somewhat noisy band, and becoming noisier all the time.

The block diagram of Fig.1 shows what's inside the ESP8266. On the left are the RF sections, including the transmitting and receiving sections, the T/R switch, an LNA (low-noise amplifier) and an RF balun for connecting to one or two antennas.

On the right is the baseband section, which includes an integrated 32-bit RISC CPU, a memory controller with both ROM and SRAM, all of the registers and sequencers for implementing a full TCP/IP stack and interfaces for SDIO (SD cards), SPI (serial peripheral interface), GPIO and I^{2}C communication with external MCUs and/or external Flash memory.

Incidentally, the RF output power in 802.11b mode is +19.5dBm, or just under 100mW. When this output is being provided in transmit mode the chip's current drain from the 3.3V supply is 215mA, corresponding to around 710mW.

In receive mode, with 1024-byte packets, the current drops to around 60mA (<200mW). The chip also has two power-saving modes: standby mode, where only the RTC and watchdog remain active (current <1mA); and deep-sleep mode, where only the RTC remains active and the current falls to below 12µA. The chip can be woken to transmit packets in less than 2ms.

The ESP-01 module

Physically, the ESP-01 module is quite small, measuring only 25 x 14.5mm, including the PCB track antenna and the 8-pin interface connector.

Fig.2 shows the complete circuit for the latest version (V2) of the ESP-01 module and there's very little in it apart from the ESP8266EX chip itself, a tiny 26MHz crystal and a 25Q80 1MB Flash memory chip. There are two LEDs, one to indicate when the module is powered up (LED1) and the other to indicate when serial data is being transmitted (LED2).

All of the connections to and from the external micro are made via CON1 at upper left.

Voltage levels

The module is designed to operate from 3.3V and should not be connected to a 5V supply. The logic inputs of the ESP8266EX are not tolerant of 5V, so if your external micro operates from 5V the interconnections need to be made via logic-level translation circuitry. We have read that applying 5V to its input pins does no harm, but this is an undocumented feature and we don't suggest you rely on it.

Default setting

Another point to note is that the ESP8266EX chips used in the latest versions of the ESP-01 module (V2) are programmed to communicate with an external PC or micro at a default rate of 115,200 bps (baud), while earlier versions were set up for 9600 bps. This can cause complications when you try to use the newer ESP-01 modules with an Arduino Uno or equivalent.

Connecting to a PC

Interfacing the ESP-01 module with a computer is quite easy. All that's needed is a USB-UART bridge module to provide a communications link with the computer (via a USB port) and also to derive power from the computer via a 5V-3.3V LDO (low-dropout) regulator to reduce the supply voltage to 3.3V.

The basic circuit needed is shown in Fig.3, although we've shown two versions of the USB-UART bridge module – one with a micro USB socket and the other with a type A socket. Both use the popular CP2102 chip, for which there's a VCP (virtual COM port) driver in most versions of Windows, Linux and macOS.

Note that although the popular USB/UART bridge modules also provide a 3.3V output, this is generally only capable of supplying 100mA or so. That's why you need to use an additional LDO regulator, like the LM1117T shown, to provide for the higher current levels needed by the ESP8266 when it's transmitting data packets.

Your PC will be able to communicate with the ESP8266 and hook up to a local Wi-Fi router and network, using a standard communications terminal

ESP8266 Features

- Wi-Fi: 802.11b/g/n
- 32-bit RISC CPU
- 512KB-16MB Flash memory
- HTTP and FTP
- IPv4
- TCP/UDP
- 17 GPIO pins
- SPI
- I^{2}S and Software I^{2}C
- 10-bit ADC

ESP8266EX
212014
PVN219

The ESP8266 is a low-power, self-contained Wi-Fi chip. The main use of the ESP8266 is to provide a Wi-Fi interface for other microcontroller devices. However, the ESP8266 IC is powerful enough to be used as a low-power computer, combined with being able to flash the firmware with your own program code using a bootloader. It has an extensive API provided on ROM, which implements various timer, hash (MD5 and SHA1), Wi-Fi and TCP/UDP functions. A list of API functions can be found at:
siliconchip.com.au/link/aaj4
siliconchip.com.au/link/aaj5

Some potential uses include:

- Remote file manager
- Web server
- Ad-hoc network
- Data logger
- Baby monitor

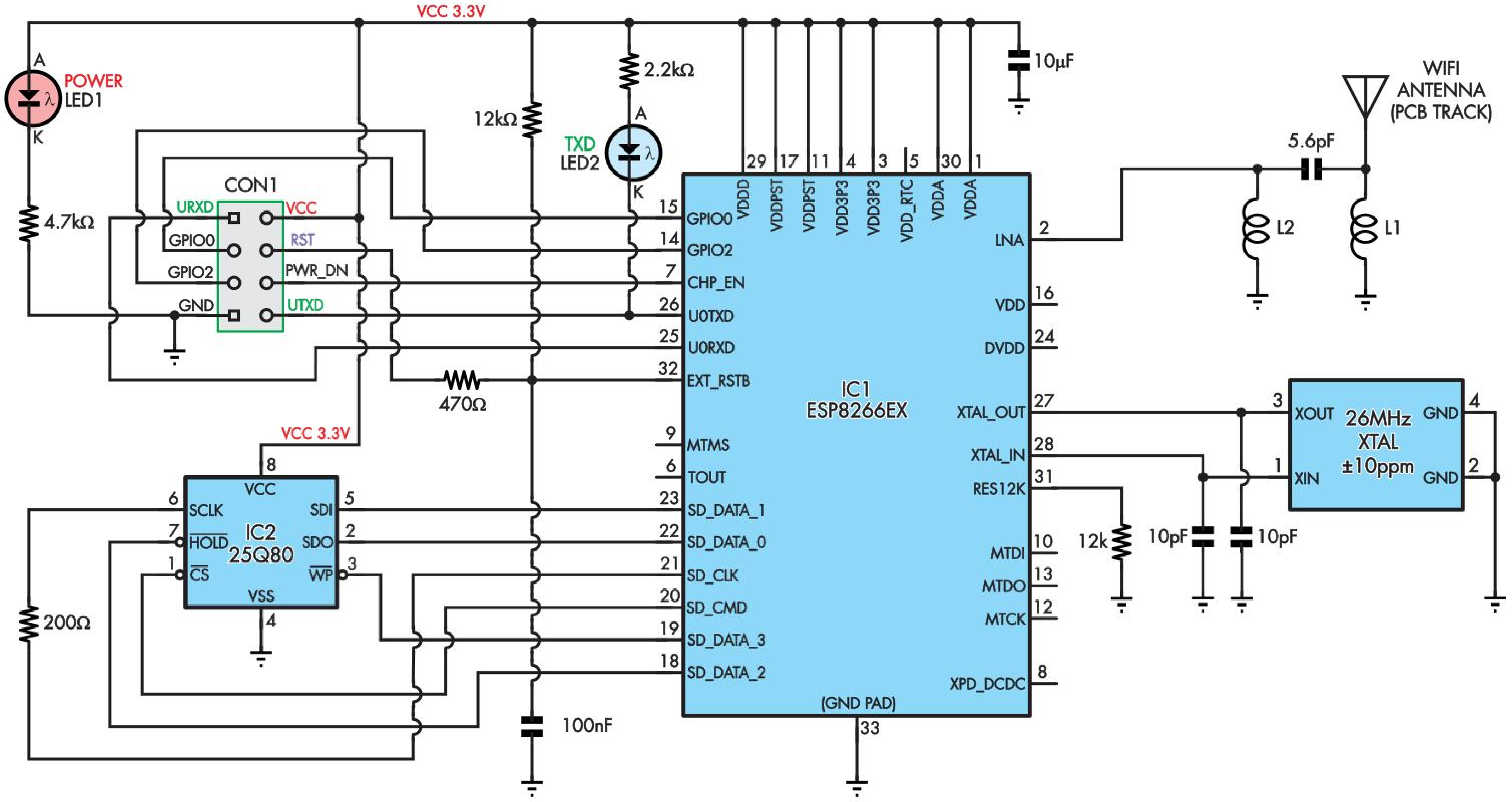

VCC 3.3V
A
POWER
LED1
K
4.7kΩ
12kΩ
2.2kΩ
TXD
LED2
A
K
10µF
WIFI
ANTENNA
(PCB TRACK)
5.6pF
L2
L1
CON1
URXD
VCC
GPIO0
RST
GPIO2
PWR_DN
GND
UTXD
470Ω
VCC 3.3V
8
VCC
6
SCLK
SDI
5
7
HOLD
IC2
25Q80
SDO
2
1
CS
WP
3
VSS
4
200Ω
100nF
29
17
11
4
3
5
30
1
VDDD
VDDPST
VDDPST
VDD3P3
VDD3P3
VDD_RTC
VDDA
VDDA
15
GPIO0
14
GPIO2
7
CHP_EN
26
U0TXD
25
U0RXD
32
EXT_RSTB
9
MTMS
6
TOUT
23
SD_DATA_1
22
SD_DATA_0
21
SD_CLK
20
SD_CMD
19
SD_DATA_3
18
SD_DATA_2
IC1
ESP8266EX
(GND PAD)
33
LNA
2
VDD
16
DVDD
24
XTAL_OUT
27
XTAL_IN
28
RES12K
31
MTDI
10
MTDO
13
MTCK
12
XPD_DCDC
8
12k
10pF
10pF
3
XOUT
26MHz
XTAL
±10ppm
GND
4
1
XIN
GND
2

Fig.2: complete circuit diagram for version 2 of the ESP-01 module. The PCB track antenna has a range of approximately 300m under good conditions with line of sight and possibly 10m, at best, indoors.

program like Tera Term. Note that this won't give your PC direct access to the wireless network, since it won't have a network driver that understands how to communicate with the ESP8266.

Programming it directly

While you can certainly use the ESP-01 module purely as a wireless 'bridge', it's also possible to program the ESP8266 directly – ie, to run some code without a separate micro. That's because the ESP8266 does have a built-in CPU of its own, together with RAM and EEPROM.

In fact, ESP8266/Arduino enthusiasts have come up with a nifty Arduino board package which allows the ESP8266 to be programmed via sketches written in the Arduino IDE, using standard Arduino functions and libraries. Information about this Arduino 'core' is available at: **https://github.com/esp8266/Arduino**

Using it with an Arduino

Connecting the ESP-01 module to an Arduino is a little more complex than you might expect, mainly because of the need to power the module with its own 5V-3.3V LDO regulator and also because logic-level translation circuitry is needed to interface between the module and an Arduino's I/O pins.

The easiest way to do this is to use a Wi-Fi module interface shield such as the Freetronics ESP1SH, which is shown in Fig.4. The shield mounts on the top of an Arduino and provides an 8-pin header socket for plugging in an ESP-01 module and an LD1117 3.3V LDO to power the module plus logic-level translation circuitry for the TX and RX data lines.

There is also a pair of pushbutton switches. S2 is for reprogramming the ESP-01's Flash memory, and the other switch (S1) is used to reset both the ESP-01 and the Arduino together.

Last, but not least, there is an 8-way-by-3 header strip, which allows you to link the level-shifted ESP-01 TX and RX lines to one of eight possible pins on the Arduino.

Link header

That link header on the ESP1SH shield is important because of the point mentioned earlier, about the latest ESP-01 modules being programmed to communicate at 115,200 bps. This a problem with the Arduino Uno and its clones because the ATmega328 CPU used in these modules has only one hardware UART, which is normally used for communication with the PC via the onboard serial/USB bridge.

To communicate with another serial device like the ESP-01, you need to use a software-driven serial port with a different pair of pins for the TX and RX lines. But these software-driven serial ports can only operate at a maximum speed of 38,400 bps. However, there is a workaround. First, you download a do-nothing sketch to the Arduino and set it running, so that it ignores the hardware UART temporarily.

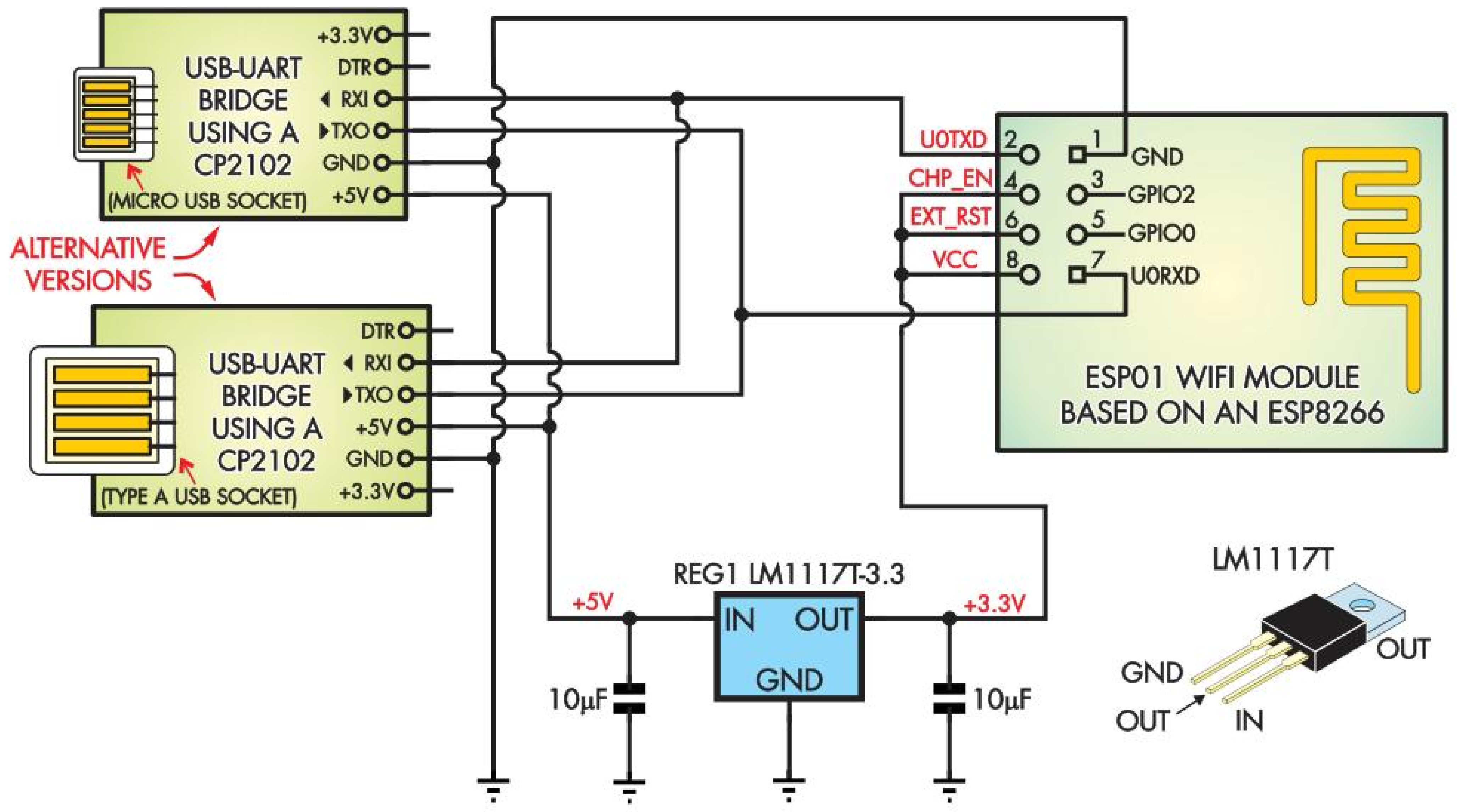
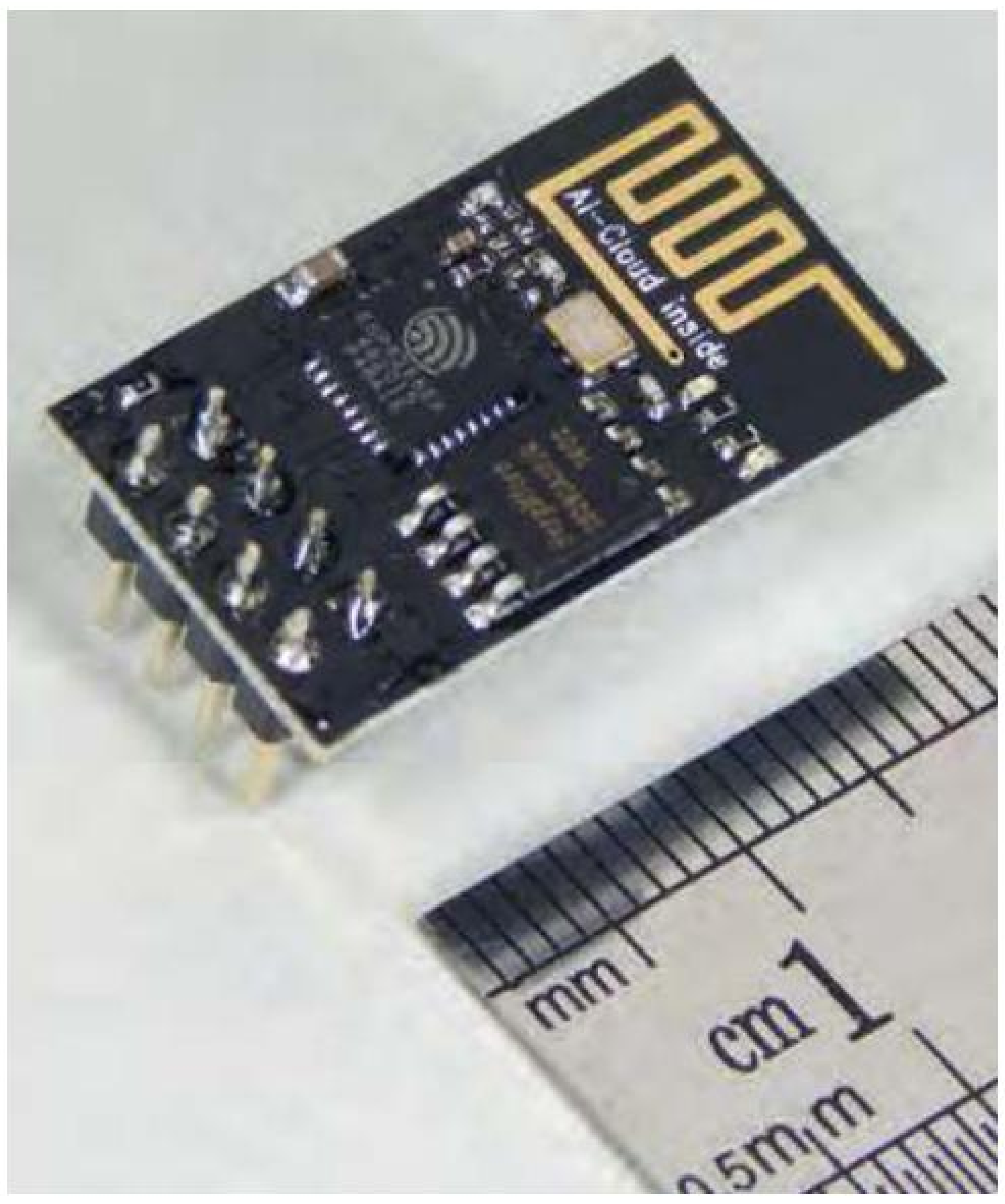

USB-UART
BRIDGE
USING A
CP2102
(MICRO USB SOCKET)
+3.3V
DTR
RXI
TXO
GND
+5V
ALTERNATIVE
VERSIONS
USB-UART
BRIDGE
USING A
CP2102
(TYPE A USB SOCKET)
DTR
RXI
TXO
+5V
GND
+3.3V
U0TXD
CHP_EN
EXT_RST
VCC
2
1
4
3
6
5
8
7
GND
GPIO2
GPIO0
U0RXD
ESP01 WIFI MODULE
BASED ON AN ESP8266
REG1 LM1117T-3.3
+5V
IN
OUT
GND
+3.3V
10µF
10µF
LM1117T
GND
OUT
OUT
IN

Fig.3: if you want to connect the ESP-01 module to a computer, all that's needed is a USB-UART bridge like the CP2102, and an LDO regulator to reduce the USB port's 5V supply voltage to 3.3V.



An enlarged view of the latest ESP-01 module. It features a few SMD components including a 26MHz crystal and 1MB of Flash memory. The GND pin is at the top-right of the PCB, while V_{CC} is at the bottom-left.

Then connect your ESP-01 module to the same hardware UART RX and TX pins (D0 and D1). You can then reprogram the ESP-01 directly from the PC so that it defaults to a data rate of 38,400bps or less, making it compatible with the software serial port.

Then reconnect the ESP-01 TX and RX lines to a different pair of pins on the Arduino and set those up as a software serial port.

Alternatively, you could simply use the hardware TX and RX pins to communicate with the ESP-01 with the limitation that you must disconnect it when re-programming the Arduino board. This will limit your use of the Serial Monitor for debugging, though.

Things are a lot easier if you use an Arduino Mega, Mega 2560R, Freetronics EtherMega or the Duinotech Mega, because these all use either the ATmega1280 or 2560 processors, both of which have a larger Flash memory plus an additional three UARTs. Each of these can provide a serial port which operates at 115,200 bps or more.

The ESP1SH shield's header strip allows you to link up the ESP-01's TX and RX lines to any serial port you wish, without the need for reprogramming. In the case of the Mega2560R, all you need to do is connect the ESP-01 TX line to pin 19 (RX1) and the RX line to pin 18 (TX1) using a pair of short male-to-female jumper leads. This is shown in both Fig.4 and the photo under it.

We'll look at what's involved in programming an Arduino Mega to use the ESP-01 module for Wi-Fi communication shortly. In the meantime, let's look at how the ESP-01 can be linked to a Micromite.

Connecting a Micromite?

How to connect an ESP-01 module to a Micromite is shown in Fig.5. Note that we still need to use an LM1117T LDO regulator to provide 3.3V to the ESP-01, since its current drain is somewhat higher than that available from the Micromite's own 3.3V regulator. But the TX and RX lines from the ESP-01 can be directly connected to the RX and TX pins of the Micromite, since no level translation is needed.

There's no problem with data rates either, providing you use the connections shown, which use the Micromite's hardware UART port (COM1). This can operate at 115,200 bps without any problems, provided you are running the Micromite at a clock frequency of 40MHz (the default), 50MHz, 30MHz or even 20MHz.

Wi-Fi via the ESP-01

Because the ESP8266 chip in the ESP-01 module is designed to communicate via standard Hayes AT modem text commands, using it to add Wi-Fi capabilities to your microcontroller project is relatively easy. All your Arduino sketch or MMBasic program needs to do is set up the ESP8266 chip using the appropriate AT commands, and then respond to the data it gets back from the ESP8266.

If this sounds a bit daunting, you can find a list of all the commands here: **http://bit.ly/pe-apr19-esp**

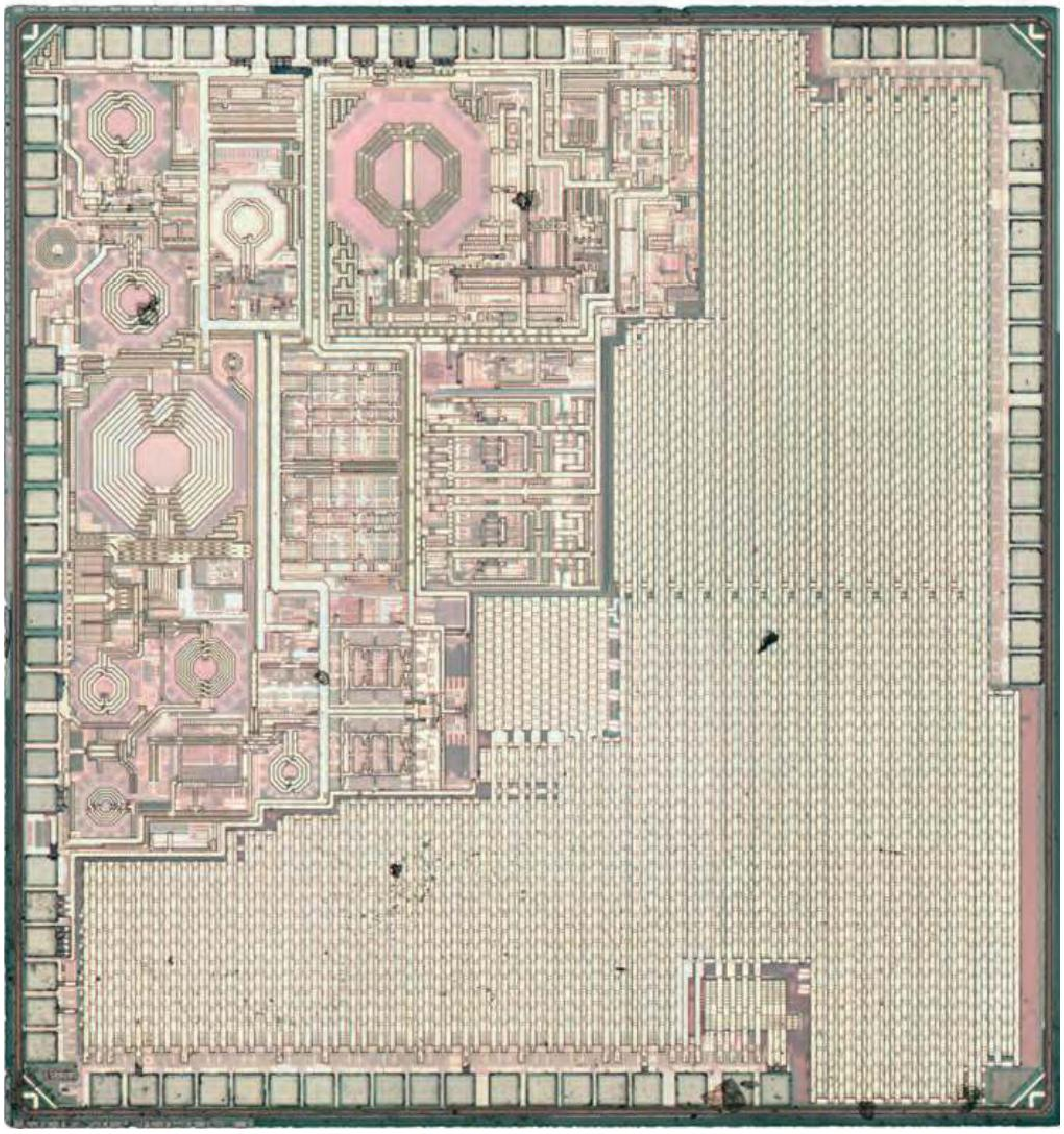
If you want to use the ESP-01 module with a Micromite, you'll get a lot of help and guidance by studying a program that Micromite guru Geoff Graham has written. The program is called **WEBServer.bas** and can be downloaded without charge from the *PE*/*EPE* website.

Using an Arduino Mega

As mentioned earlier, the easiest Arduino to connect with the ESP-01 module is the Mega. It's especially easy if you use a Wi-Fi shield like the Freetronics ESP1SH to interface between the two, as shown in the photo overleaf.

The ESP1SH shield makes most of the connections between the ESP-01 and the Arduino Mega, when you plug it in.

The only additional connections you need to make are between the level-translated TX and RX lines of the ESP-01 (the uppermost and lowermost rows of pins on the shield's 8x3



An enlarged photo of the silicon die and metal layers of an ESP8266 (a variant of the ESP8089). The RF section is at upper left and takes up a large portion of the chip. The area below and right is memory while the I/O pads are along the edges. http://bit.ly/pe-zepto

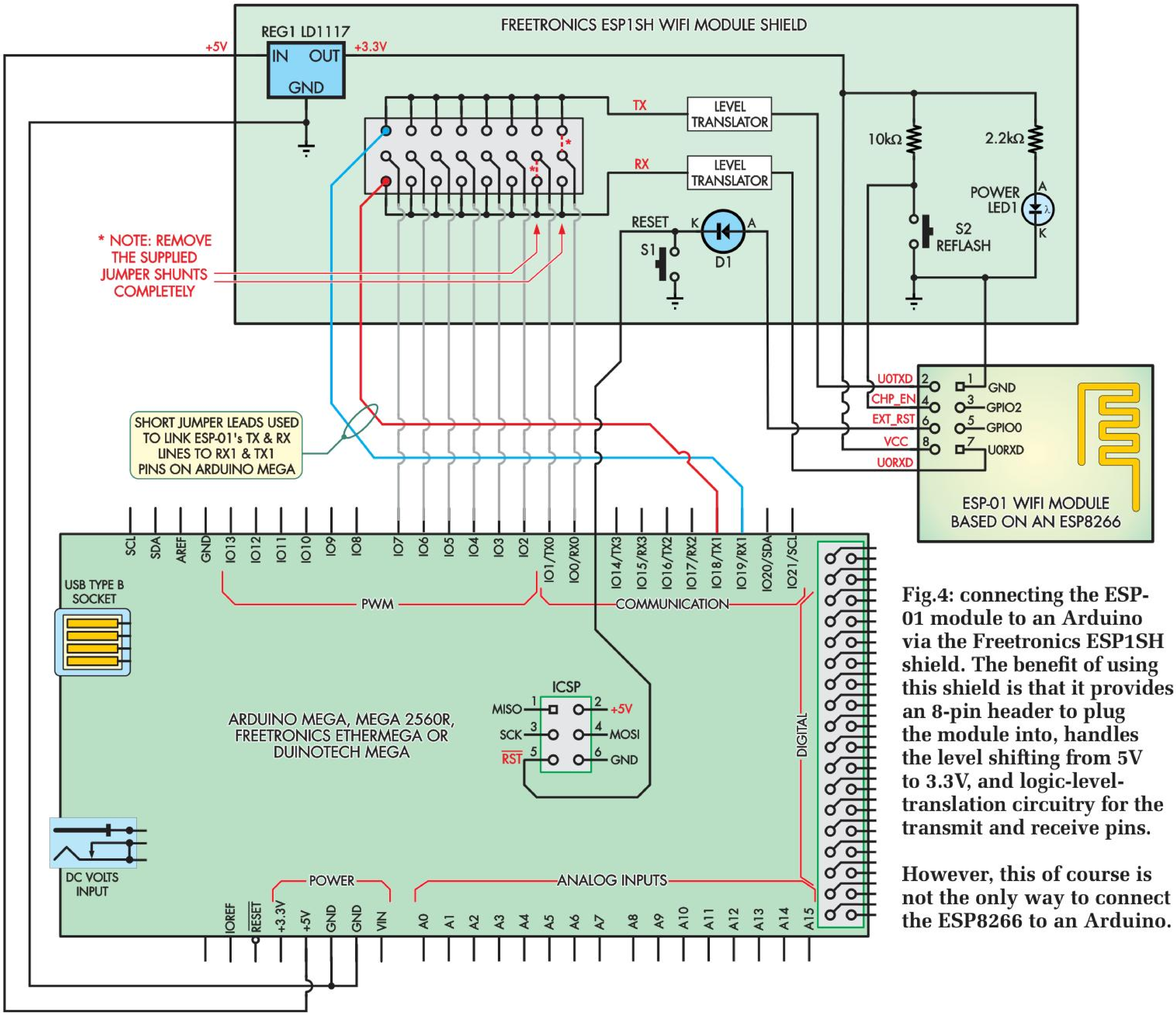

FREETRONICS ESP1SH WIFI MODULE SHIELD
REG1 LD1117
IN
OUT
GND
+5V
+3.3V
TX
RX
LEVEL TRANSLATOR
LEVEL TRANSLATOR
RESET
S1
K
A
D1
10kΩ
2.2kΩ
POWER LED1
S2 REFLASH
* NOTE: REMOVE THE SUPPLIED JUMPER SHUNTS COMPLETELY
SHORT JUMPER LEADS USED TO LINK ESP-01's TX & RX LINES TO RX1 & TX1 PINS ON ARDUINO MEGA
U0TXD
CHP_EN
EXT_RST
VCC
U0RXD
GND
GPIO2
GPIO0
U0RXD
ESP-01 WIFI MODULE BASED ON AN ESP8266
SCL
SDA
AREF
GND
IO13
IO12
IO11
IO10
IO9
IO8
IO7
IO6
IO5
IO4
IO3
IO2
IO1/TX0
IO0/RX0
IO14/TX3
IO15/RX3
IO16/TX2
IO17/RX2
IO18/TX1
IO19/RX1
IO20/SDA
IO21/SCL
PWM
COMMUNICATION
USB TYPE B SOCKET
ICSP
MISO
SCK
RST
+5V
MOSI
GND
ARDUINO MEGA, MEGA 2560R, FREETRONICS ETHERMEGA OR DUINOTECH MEGA
DIGITAL
DC VOLTS INPUT
POWER
ANALOG INPUTS
IOREF
RESET
+3.3V
+5V
GND
GND
VIN
A0
A1
A2
A3
A4
A5
A6
A7
A8
A9
A10
A11
A12
A13
A14
A15

Fig.4: connecting the ESP-01 module to an Arduino via the Freetronics ESP1SH shield. The benefit of using this shield is that it provides an 8-pin header to plug the module into, handles the level shifting from 5V to 3.3V, and logic-level-translation circuitry for the transmit and receive pins.

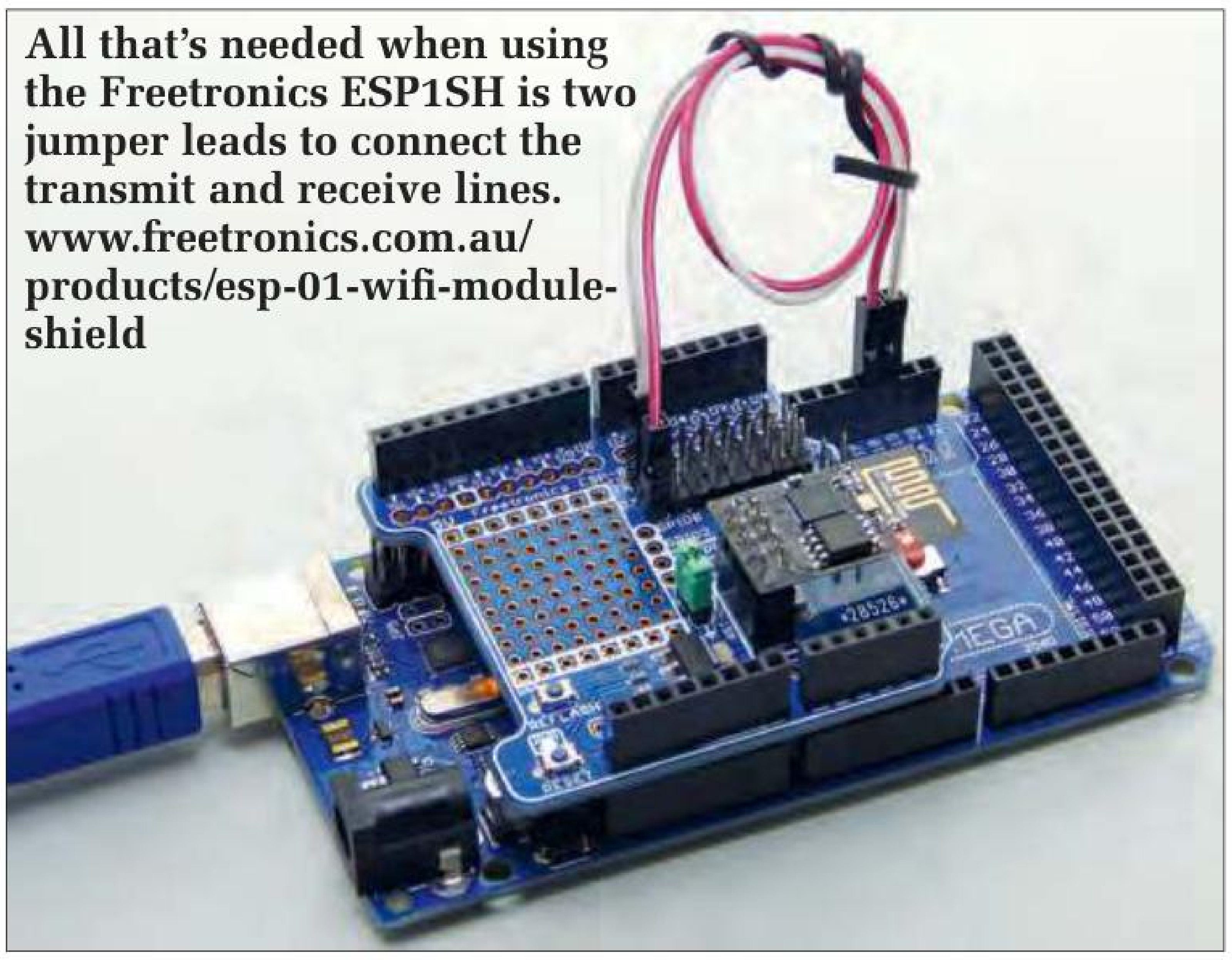
However, this of course is not the only way to connect the ESP8266 to an Arduino.

programming header) and the IO19/RX1 and IO18/TX1 pins of the Arduino Mega. As shown in the photo below and in Fig.4, these added connections are made by short male-to-female jumper leads.

Just remember to remove the jumper shunts which come with the ESP1SH shield, because these can only be used to connect the ESP-01's TX and RX lines to the Mega's IO0/RX0 and IO1/TX0 hardware UART (or to pins IO2-IO7 for using a software serial port).

The jumper lead from one of the uppermost TX pins of the shield's 8x3 header needs to be connected to the Mega's IO19/RX1 socket (blue lead in Fig.4), while the lowermost RX pins on the header should be connected to the Mega's IO18/TX1 socket (red lead in Fig.4). If you get these two connections swapped, your Mega won't be able to communicate with the ESP-01 module.

Programming the Mega for Wi-Fi communication via the ESP-01 is fairly easy. You'll find quite a few Arduino



All that's needed when using the Freetronics ESP1SH is two jumper leads to connect the transmit and receive lines. www.freetronics.com.au/products/esp-01-wifi-module-shield

Links for using the ESP-01/ESP8266

https://espressif.com
http://bit.ly/pe-ESP8266-01
https://forum.arduino.cc/index.php?board=11.0
http://bbs.espressif.com
www.electrodragon.com/w/Wi07c
http://bit.ly/pe-ESP8266-02
www.sparkfun.com/products/13678
https://en.wikipedia.org/wiki/ESP8266
https://github.com/espressif
https://github.com/esp8266/Arduino
https://github.com/tttapa/ESP8266
https://github.com/acrobotic/Ai_Docs
https://github.com/espressif/esp8266_mp3_decoder/

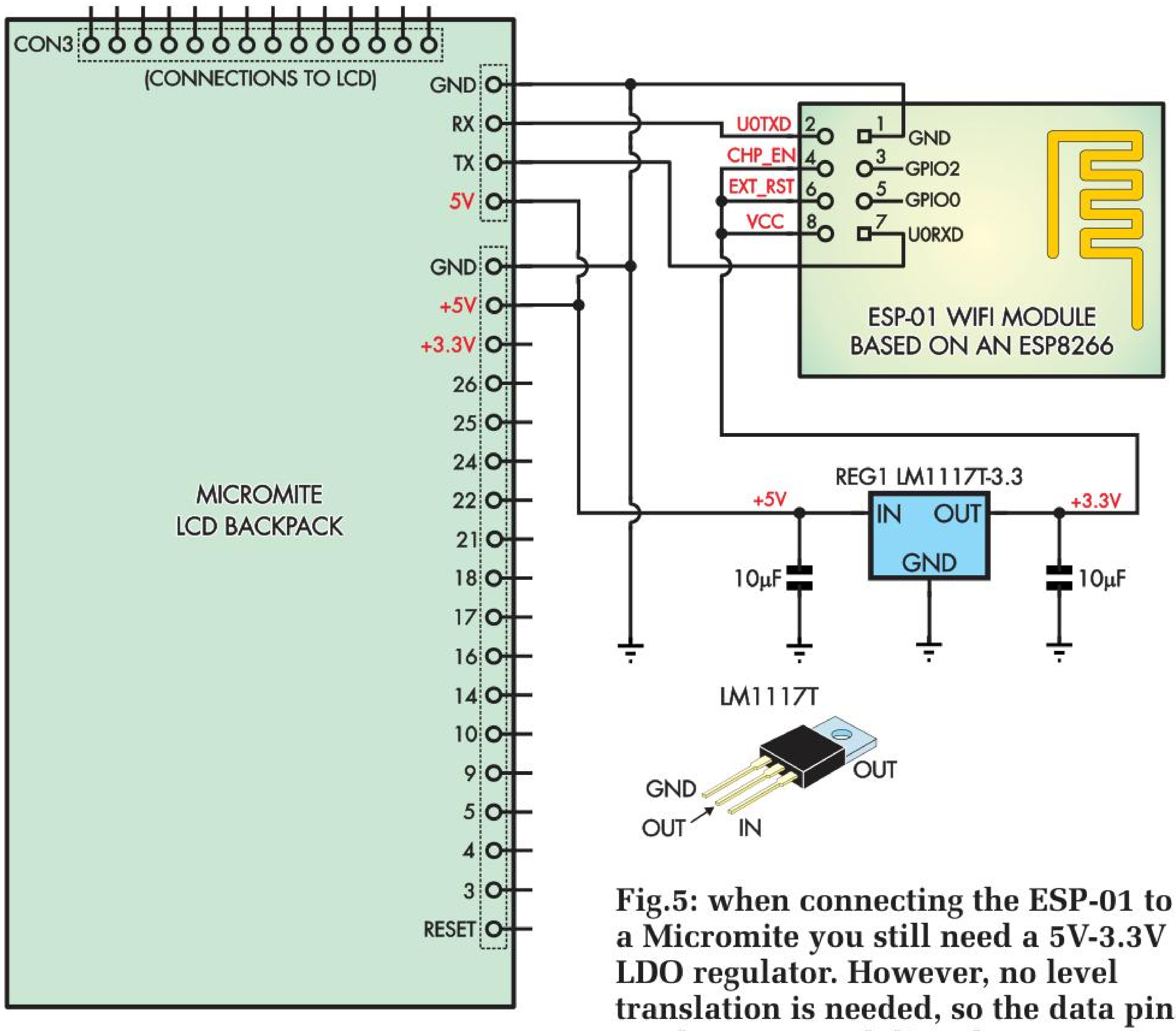


Fig.5: when connecting the ESP-01 to a Micromite you still need a 5V-3.3V LDO regulator. However, no level translation is needed, so the data pins can be connected directly.

sketches on the web which illustrate how you can use the ESP8266, and there's also a Wi-Fi Library available on the main Arduino website (see **www.arduino.cc/en/Reference/Libraries**).

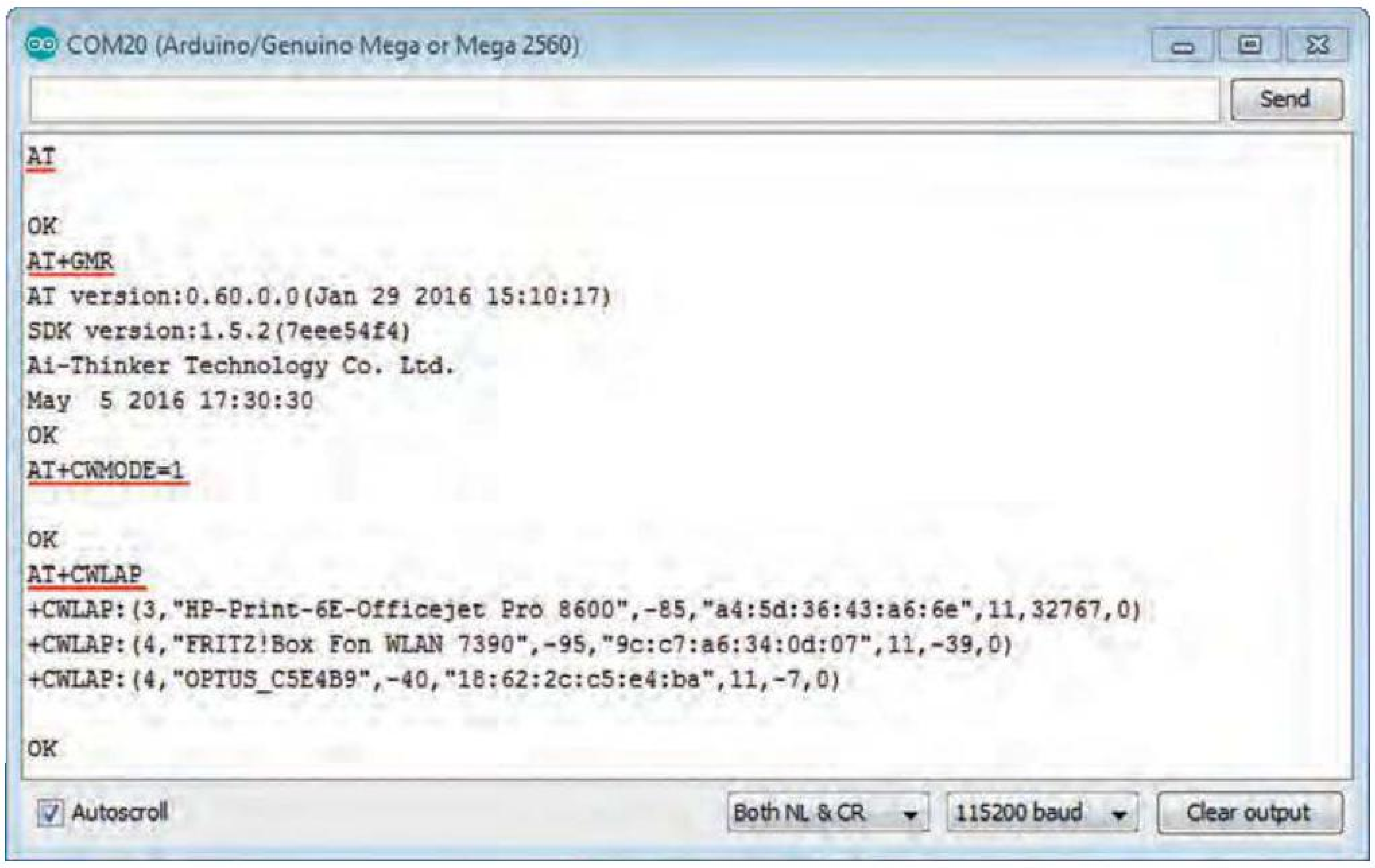
To get you started, I've adapted a simple pass-through sketch that I found on one of the websites so that it's capable of running straight away on the Mega/ESP1SH/ESP-01 setup. The sketch makes the Mega behave as a relay station or mirror between your computer and the ESP-01 and its ESP8266.

So any AT commands sent from your computer via the Arduino IDE's Serial Monitor utility are relayed to the ESP8266. Likewise, any responses from the ESP8266 are relayed back to the IDE's Serial Monitor. This makes it easy to try sending various AT commands to the ESP-01 and to see its responses.

The sketch is listed at the end of this section and you can also download it from the *PE*/*EPE* website.

The screen grab shown in Fig.6 shows how this works. The lines underlined in red are those with the AT commands sent to the ESP-01/ESP8266, while those without any underlining show the responses coming back from it. The first AT command is basically just an enquiry to see if the ESP8266 is awake, with it returning 'OK' if it is.

Similarly, the command AT+GMR resets the ESP8266 and also gets it to respond with information concerning its firmware.



```
AT

OK
AT+GMR
AT version:0.60.0.0(Jan 29 2016 15:10:17)
SDK version:1.5.2(7eee54f4)
Ai-Thinker Technology Co. Ltd.
May  5 2016 17:30:30
OK
AT+CWMODE=1

OK
AT+CWLAP
+CWLAP:(3,"HP-Print-6E-Officejet Pro 8600",-85,"a4:5d:36:43:a6:6e",11,32767,0)
+CWLAP:(4,"FRITZ!Box Fon WLAN 7390",-95,"9c:c7:a6:34:0d:07",11,-39,0)
+CWLAP:(4,"OPTUS_C5E4B9",-40,"18:62:2c:c5:e4:ba",11,-7,0)

OK
```

Fig.6: the sample serial pass-through program running on an Arduino Mega. This program merely repeats data to and from the ESP-01 module.

Then the command AT+CWMODE=1 directs the ESP8266 to assume Wi-Fi client mode, as opposed to access point mode (mode 2) or client/access point mode (mode 3).

The additional command shown in Fig.6 is AT+CWLAP, which asks the ESP8266 to list any Wi-Fi access points currently available within its range. Of the three lines you can see in Fig.6, the last line corresponds to my office network router, while the other two are routers or peripherals in nearby homes.

The other point to note from Fig.6 is that the Arduino Mega I was using at the time had been allocated to virtual COM port 20 (top left), while the IDE Serial Monitor was communicating with the Mega and ESP8266 at 115,200 baud (bps).

Why not try programming the ESP-01 Wi-Fi module yourself?

```
// Sample program from Fig.6.
void setup() {
  Serial.begin(115200);
  Serial1.begin(115200);
}
void loop() {
  if (Serial.available())
    Serial1.write(Serial.read());
  if (Serial1.available())
    Serial.write(Serial1.read());
}
```

Loading your own code onto the ESP8266

If you do this, you will lose the AT command set capabilities, since these are provided by the default code loaded into the ESP8266 processor. But it does allow the ESP-01 to become an independent module without the need for many external components.

The best demonstration of this is in our *NTP Clock* project article on page 14 of this issue, where we turned an ESP-01 into a device which pretends to be a GPS module, supplying NMEA data from its serial port and a 1pps signal – but it actually gets the time, date and location data from NTP and location servers on the Internet. This allows you to use a GPS-synchronised clock in a location where a GPS signal is not available.

We won't go into great detail about how to program the ESP8266 yourself here, as you can refer to that article on page 14 and examine its source code (which can be downloaded from the *PE*/*EPE* website) to see how it works.

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MIDI Ultimate Synthesiser

Part 3 | by Paul Cooper | soundtronics.co.uk

Last month, you should have successfully built and tested the VCOs, mixer, VCF and the power supply. This month, we continue with the main PCB, working on the VCA, echo, noise and headphone amplifier sections. This is an exciting stage, although we are only halfway through the build, you will be able to start creating sounds.

First, a reminder of a useful PCB assembly aid covered in *Part 2* – use 25mm standoffs on the pot side of the PCB with 30mm M4 screws and lock nuts. These provide clearance for the component leads and the pots/switches (see *Part 2*, Fig.28). If you have purchased your components from Soundtronics.co.uk then you will find that the components for each section on the PCB are bagged individually. The complete parts list was published in the February 2019 issue, but as an aid, the VCA, echo and headphone amplifier all have part designators beginning with '5xx'. The noise generator has the following parts:

Resistors (all 0.25W 1% metal film)

R3	1kΩ
R12	3kΩ
R14	20kΩ
R4, R16	100kΩ
R1, R17, R18	470kΩ
R13	1MΩ

Capacitors

C1, C3, C5, C7	100nF 5mm X7R dielectric radial ceramic
C2, C9	Radial electrolytic 10µF 25V

Other

Q1 2N3904 transistor NPN TO-92 60V
U1 Dual op amp BiFET TL072CP
P1 20kΩ Multi-turn cermet preset top adjust SIL
8-pin turned-pin 0.3-inch DIL IC socket

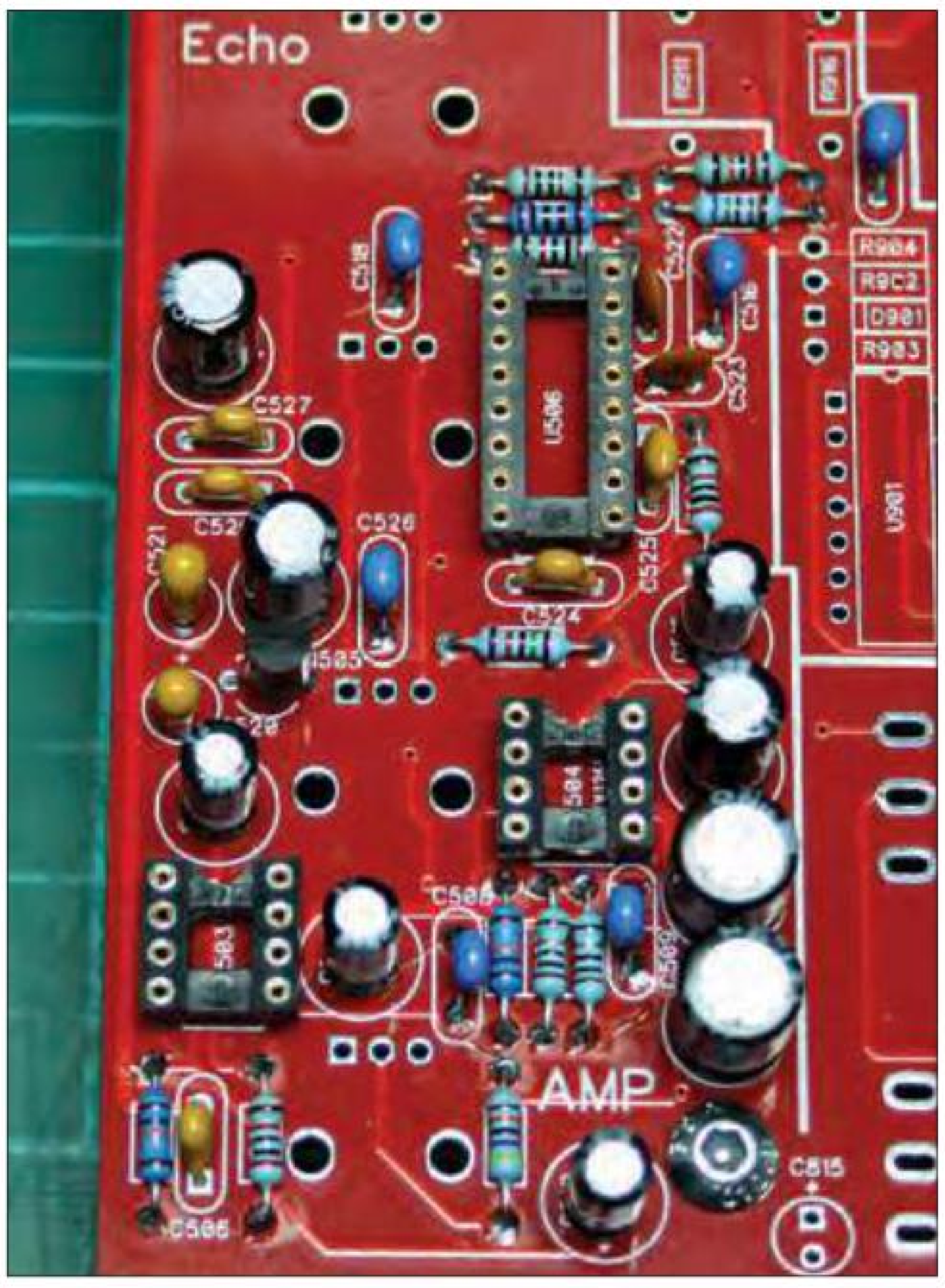
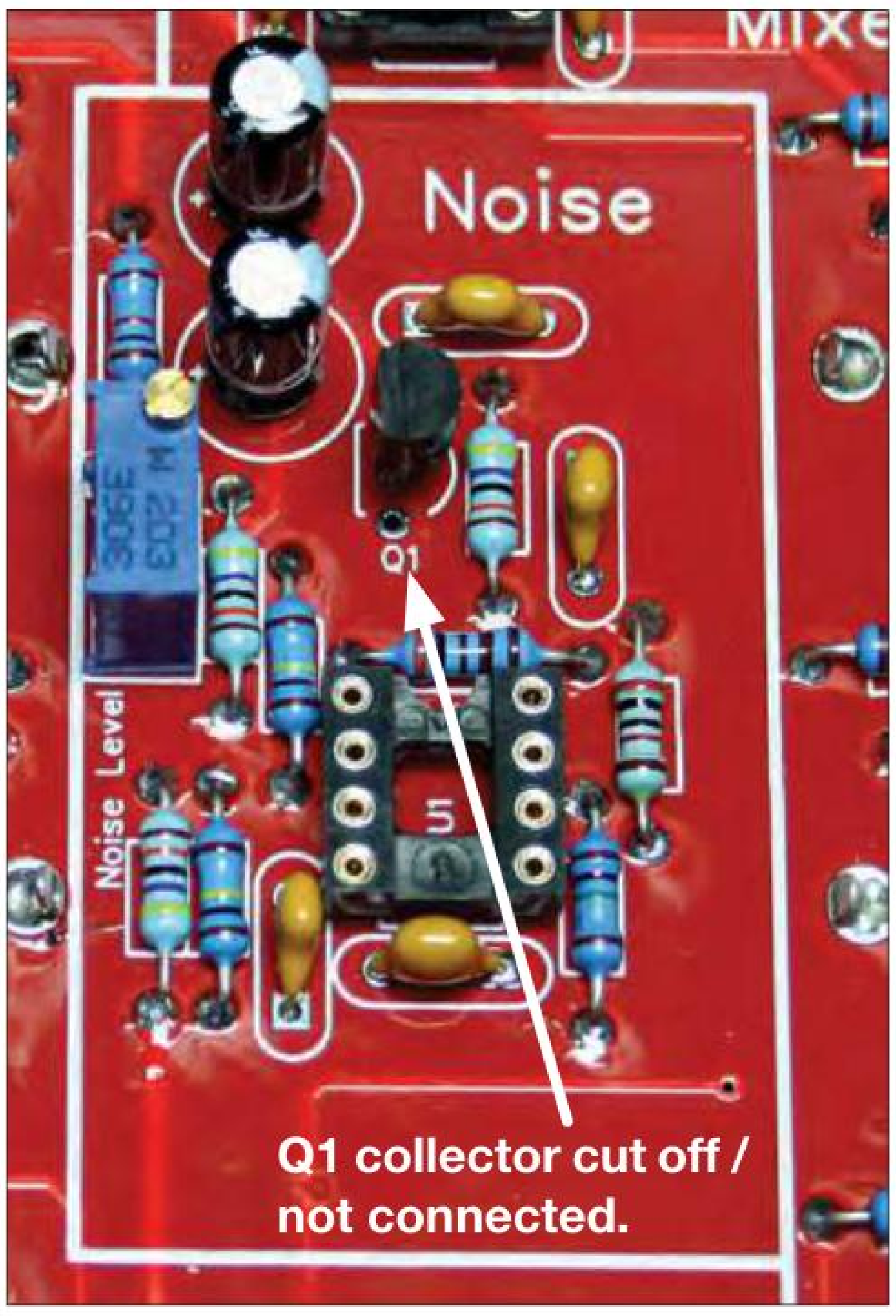


Fig.44. Echo and headphone amplifiers components, C519 is located just outside the border.



Q1 collector cut off / not connected.

Fig.45. Noise components, note the collector lead of Q1 is cut off / not connected.

While it is not critical which section you choose to populate first with components, the echo and headphone amplifier are best done together because they share the same PCB section (Fig.44).

There are relatively few components for the white noise generator, but do remember to cut off the collector lead from transistor Q1 (Fig 45). The reason for this is explained in the circuit description later in this article.

That just leaves the VCA components (Fig.46) to solder in before we move onto the pots and switches.

The technique for soldering the pots and switches is exactly the same as described in the last issue (*Part 2*). This time, however, we only have three toggle switches for the VCA and seven pots to solder in. The pots 'click' into the PCB, and the switches are mounted on the aluminium back panel (Fig.47). Fig.48 shows the PCB ready to lower onto the back panel, which has been pre-prepared with M4 screws and spacers.

Place spacers and M4 nuts on the protruding M4 studs and hand tighten to ensure an even 10mm gap between the PCB and back panel (Fig.49). Then solder the three toggle switches, followed by the potentiometers using the same technique described last month (see Fig.35).

After assembly of this month's four sections (modules), there will be a

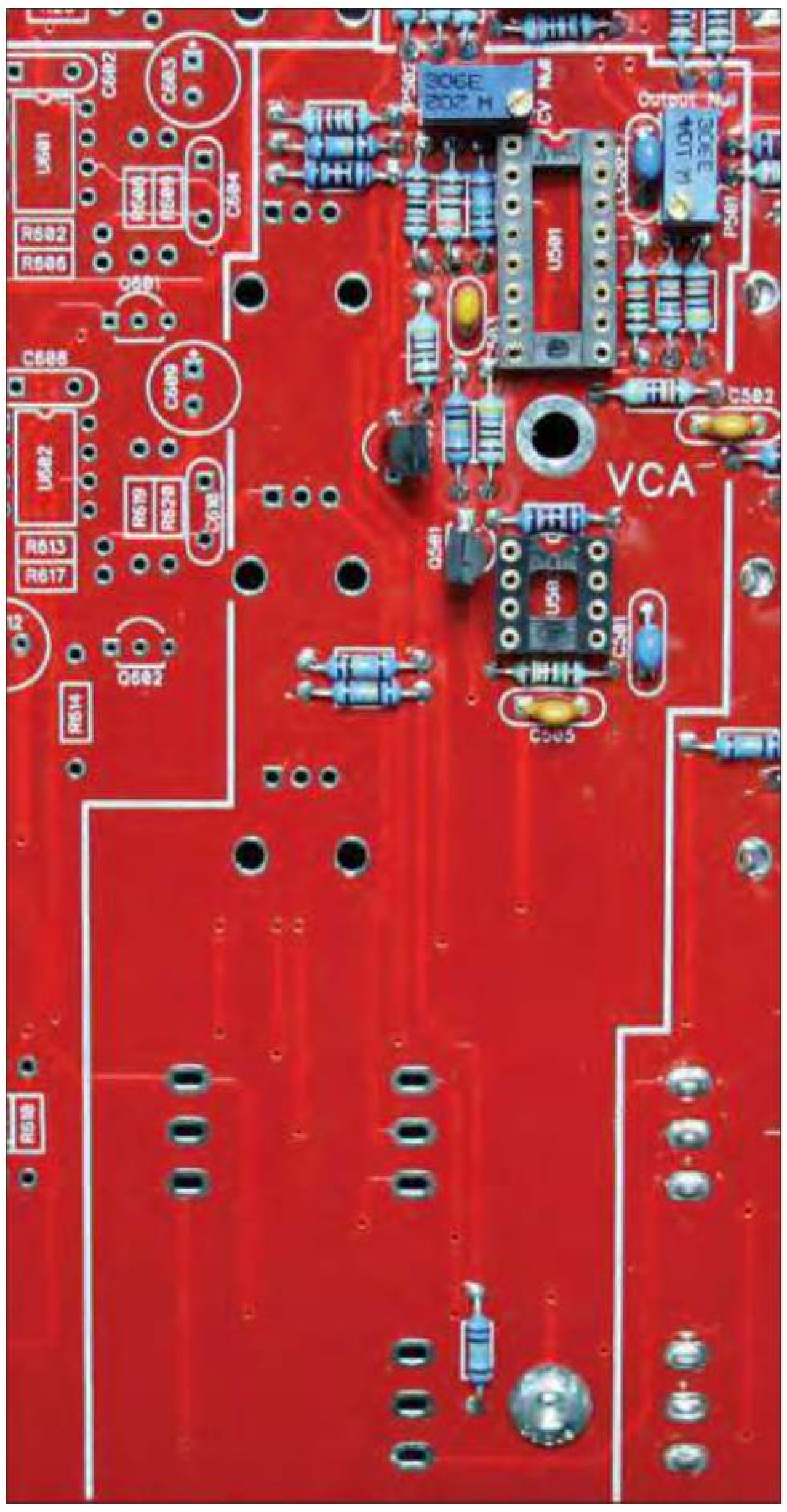


Fig.46. VCA components – don't miss R506 near the bottom edge of the PCB.

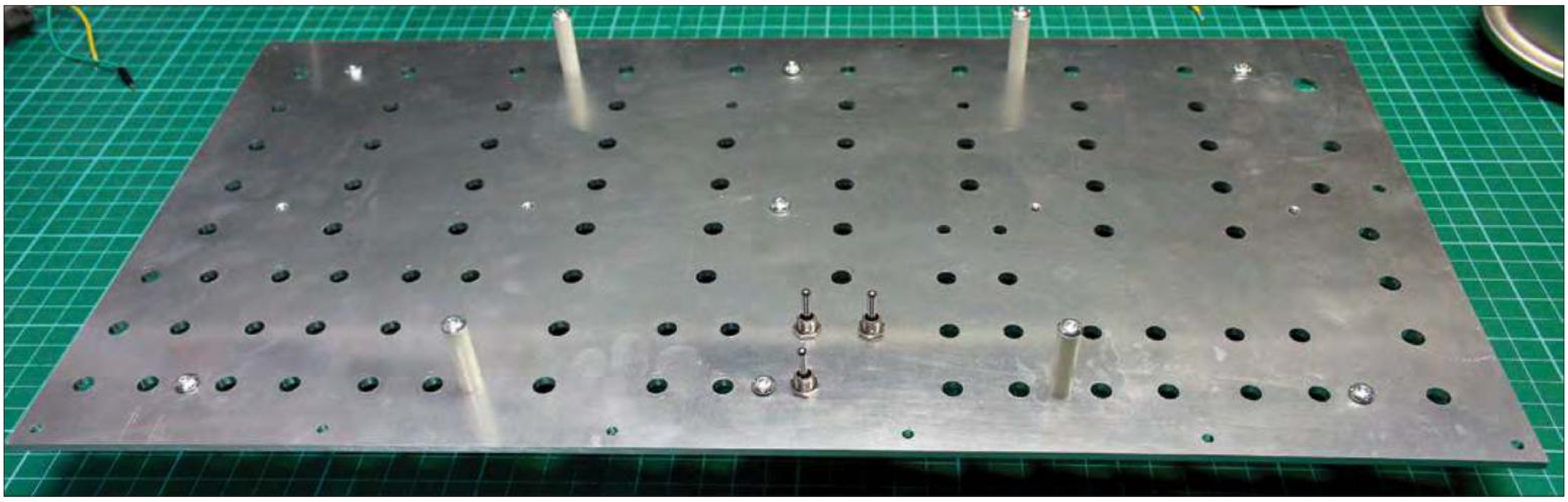


Fig.47. The three VCA toggle switches, retained temporarily with a lock nut.

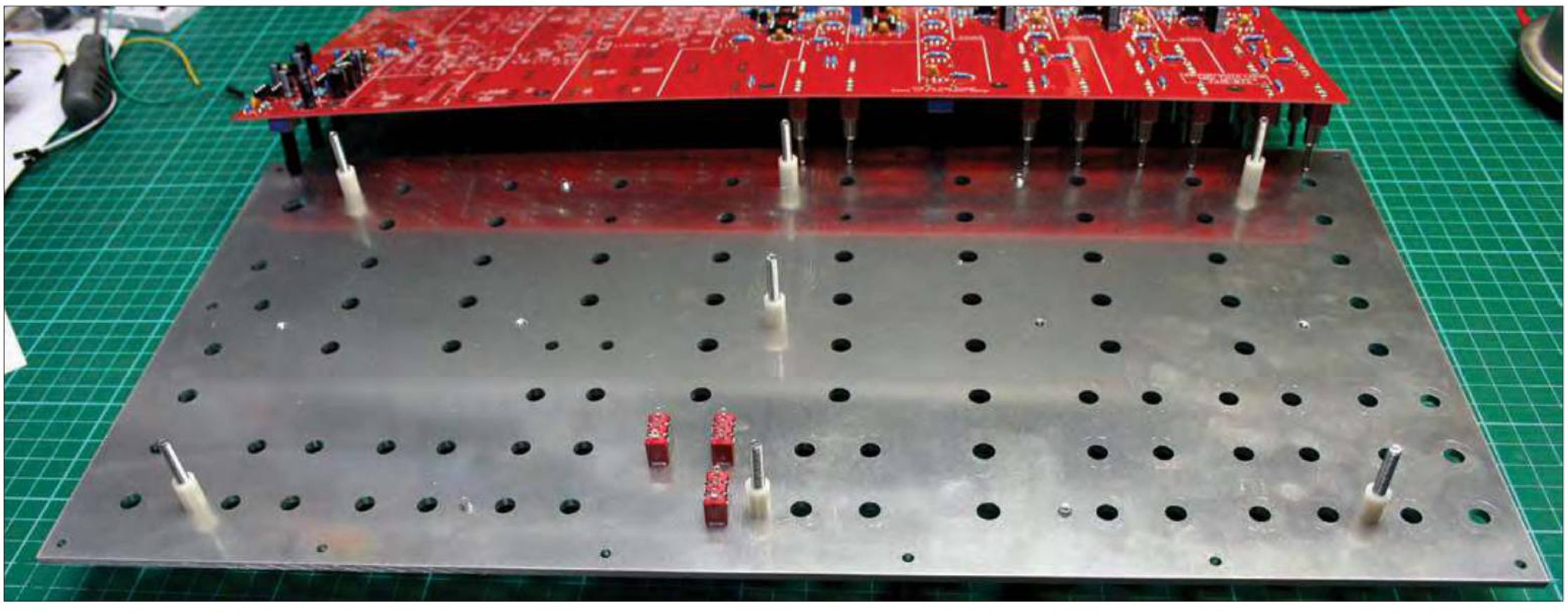


Fig.48. Ready to drop the PCB in place, the seven pots are 'clicked' in position on the PCB.

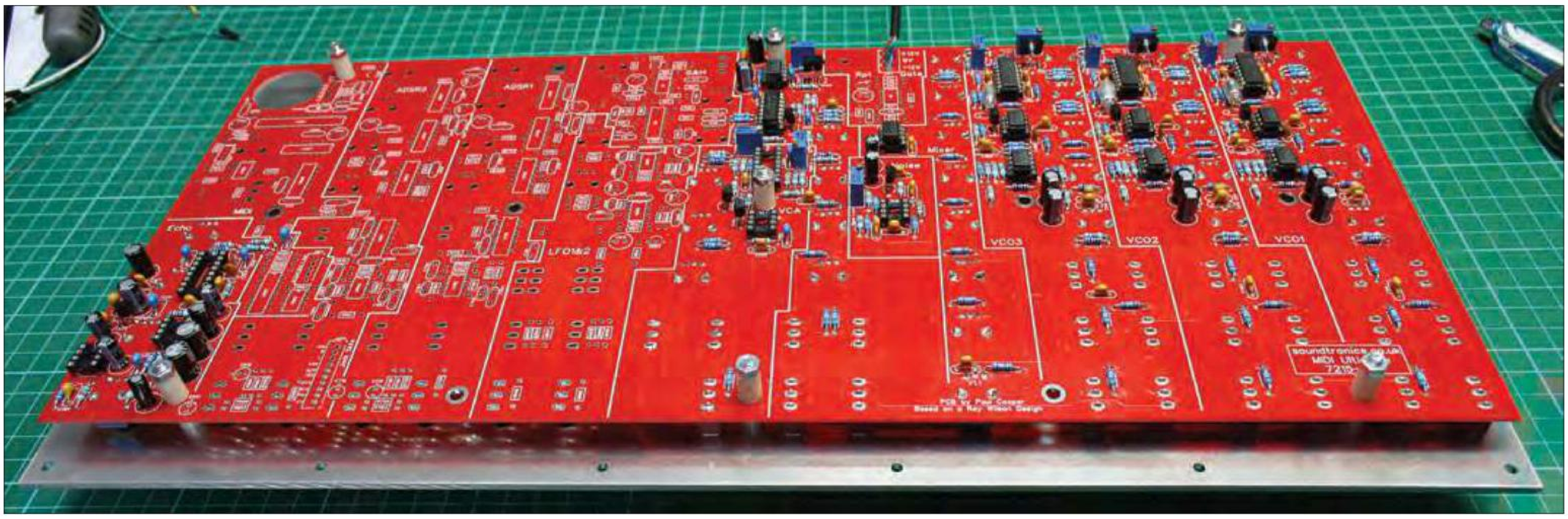


Fig.49. The PCB has been retained in position prior to soldering the pots and switches.

complete audio path from the waveform generators (VCOs and noise), through the mixer, VCF and echo, and finally to the headphone amplifier. Fig.5 from *Part 1* graphically shows this – follow the solid green arrows. This does mean we can now start to become familiar with the synth controls. To do this, the stereo jack socket for the headphones output needs connecting up. In the final build, all of the jack sockets, including the headphone jack are soldered onto a dedicated PCB on the rear panel. For now, we can simply wire the jack socket to JST connector J902. Solder J902 into position noting its orientation (Fig.50).

The JST lead assembly is supplied pre-made, so it can be plugged straight into J902 (Fig.51). For now, we only need the first three wires connected to Gnd, L and R (ground, left and right). The remaining seven wires can be tied back and insulated with tape.

Now solder the wires to the stereo jack socket. This is a switched socket with contacts that open when a jack plug is inserted. We don't need the switching function, so only the three soldered connections are required (Fig.52).

The *MIDI Ultimate* is a monophonic instrument, so it does not matter which way around L and R are connected to the jack socket; but by convention, the left channel (white wire) is the tip of the jack plug.

You will now be able to directly listen to the audio output of the synth using a set of headphones. If you want more volume, then wire a mono jack socket to the line output (yellow wire) on J902 so you can plug in an external amplifier.

Before we test what we have built so far, let's describe the circuits for VCA, echo, headphone amplifier and noise generator.

Voltage Controlled Amplifier (VCA)

The VCA signal input comes from the output of the low-pass filter and its output is fed direct to the input of the echo effect module. (I recommend reading Jake Rothman's *Audio Out* articles on VCA techniques, including the use of transconductance amplifiers – *EPE*, September and November 2018). The function of the VCA is to vary the amplitude of the audio signal from the VCF using a control voltage. The control voltage can originate from:

- Either of the low-frequency oscillators
- Either of the envelope generators
- The sample and hold (S&H)
- MIDI auxiliary channel
- Various combinations of the above.

In addition, there is manual initial-level control (VR502) of the base amplification level.

The VCA circuit in Fig.53 consists of three main areas:

1. U502.1 non-inverting control voltage mixer, similar to that at the front end of the VCF described last month. The output of U502.1 is the sum of the voltages of: VR501 (ADSR), the initial-level pot VR502, VR503 (LFOs) and the R506 (S&H / MIDI Aux).
2. U502.2 / Q501 / Q502 control-voltage-to-exponential-current converter, which (again) is near identical to the VCF
3. U501.1 current-controlled amplifier at the output. The positive current

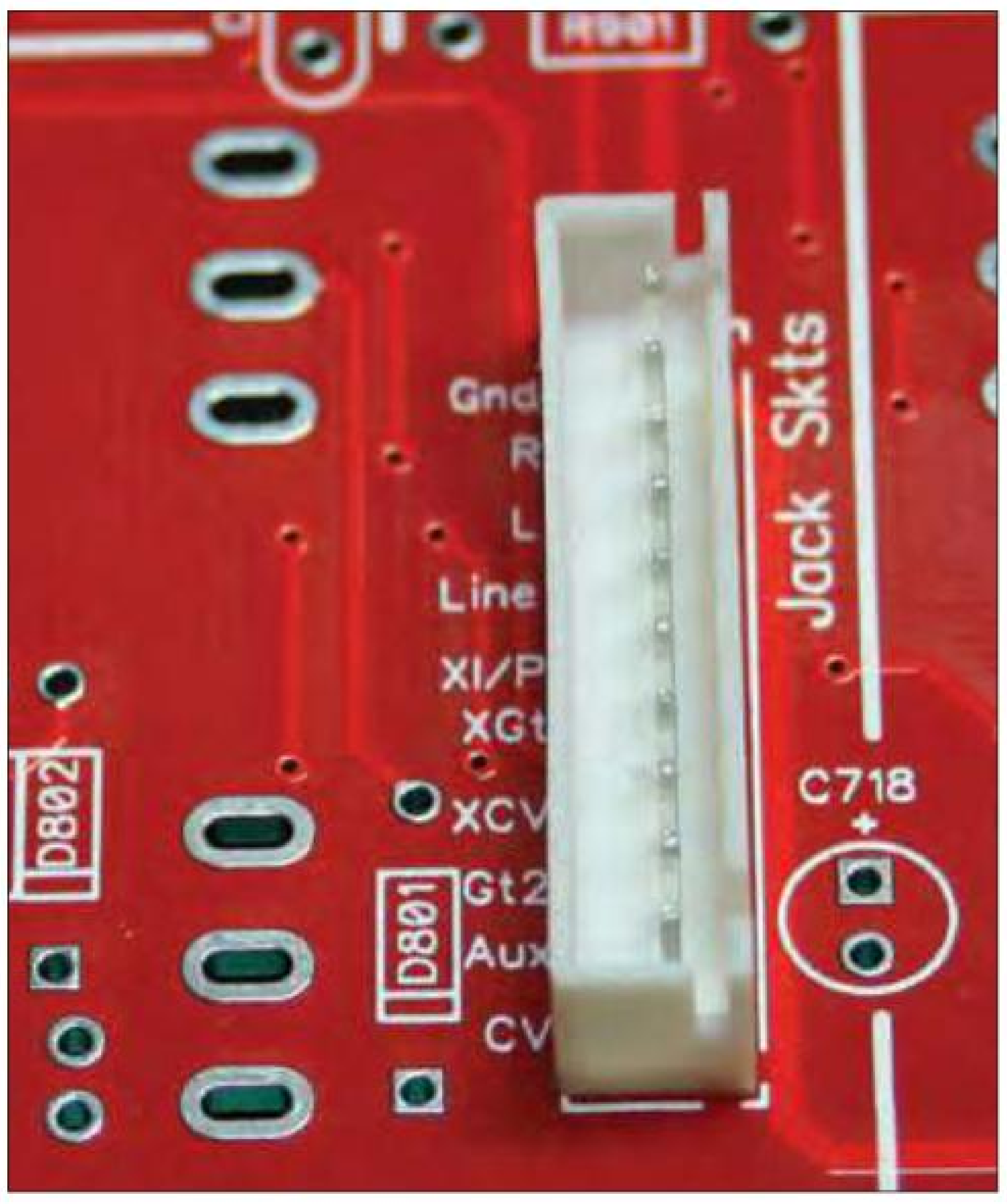


Fig.50. J902 jack socket header – note the orientation.

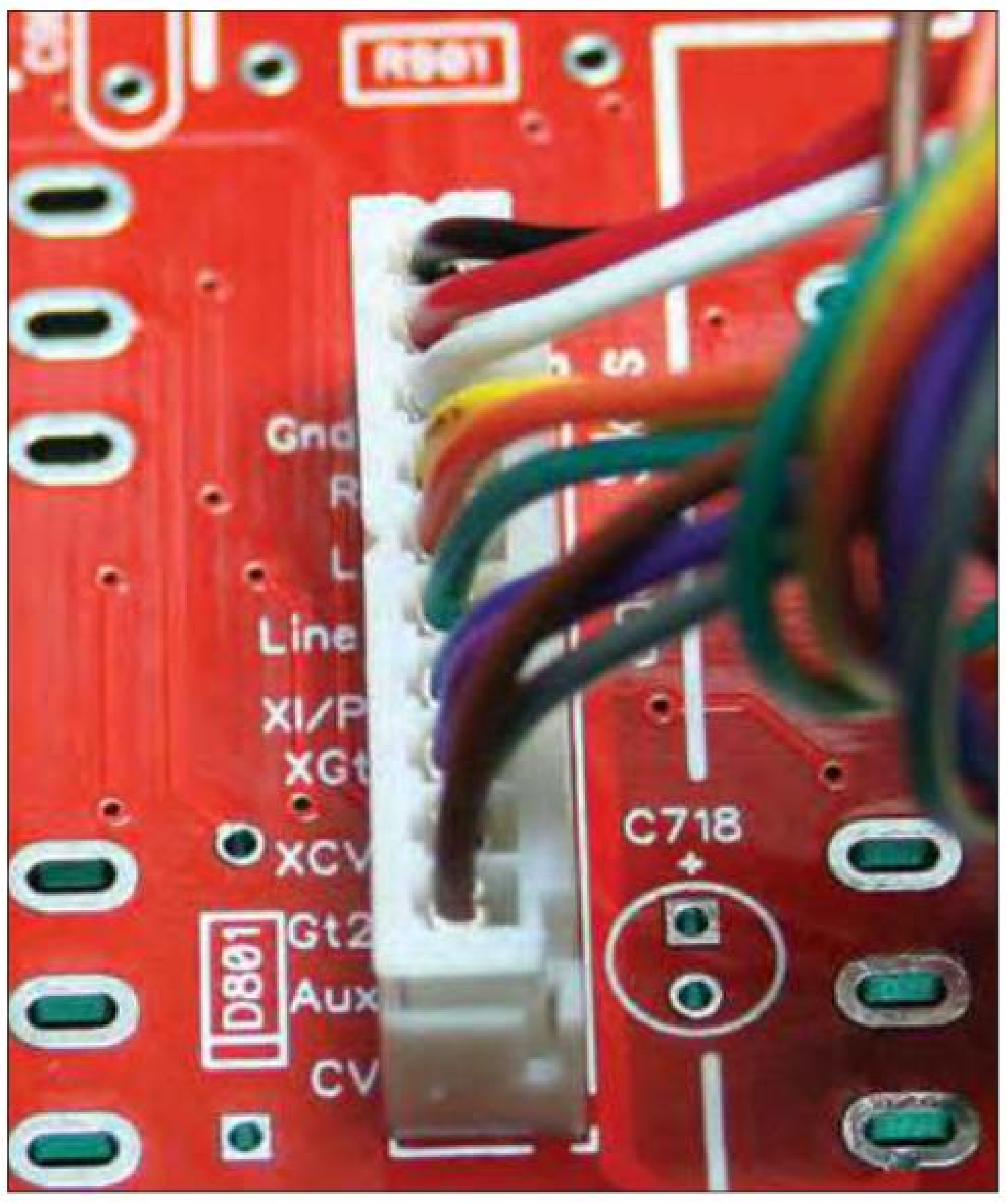


Fig.51. The black, red and white wires are needed for the headphone jack.

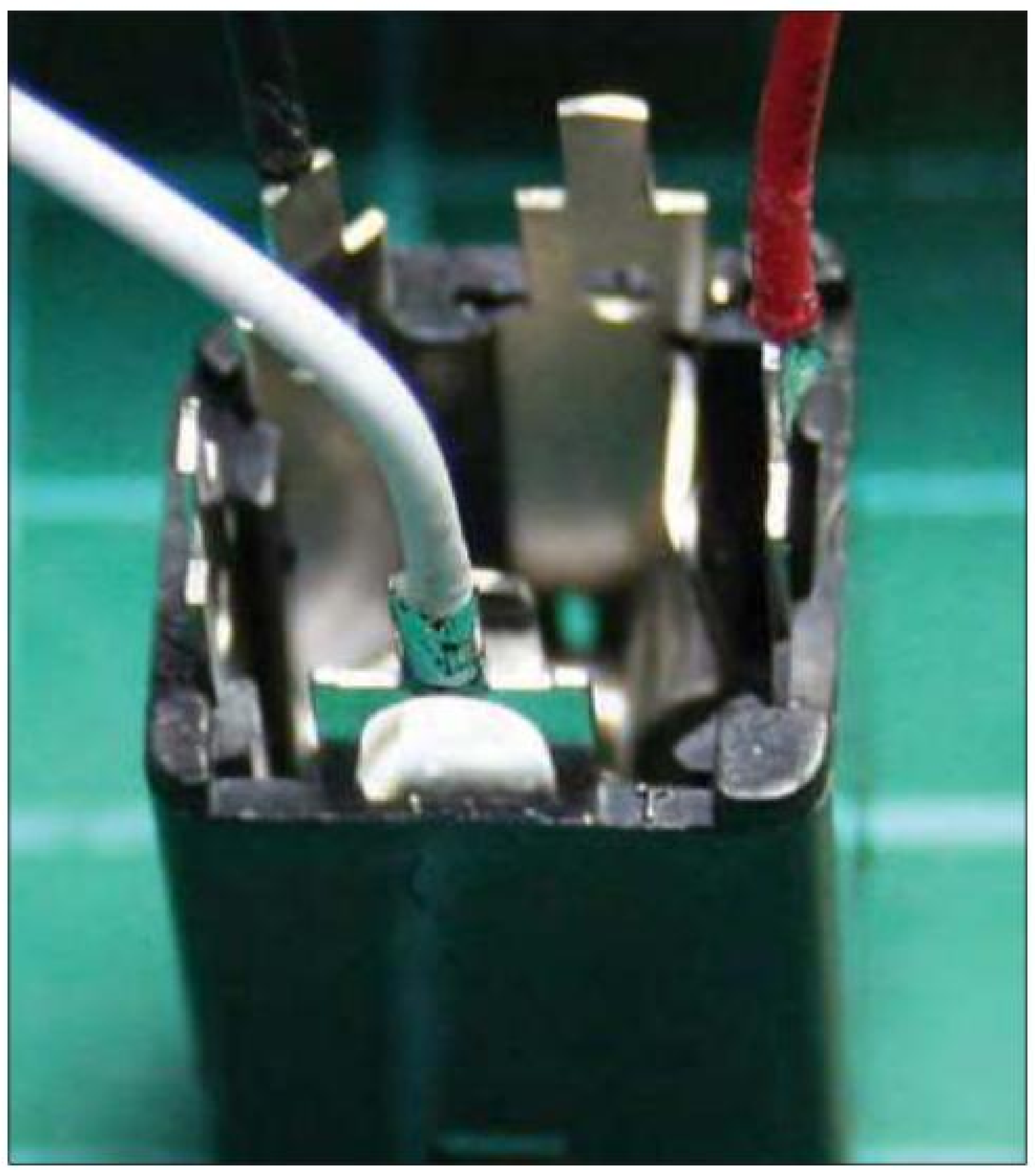


Fig.52. The black ground wire connects to the lug on the flat corner, audio left (white) and audio right (red) as shown.

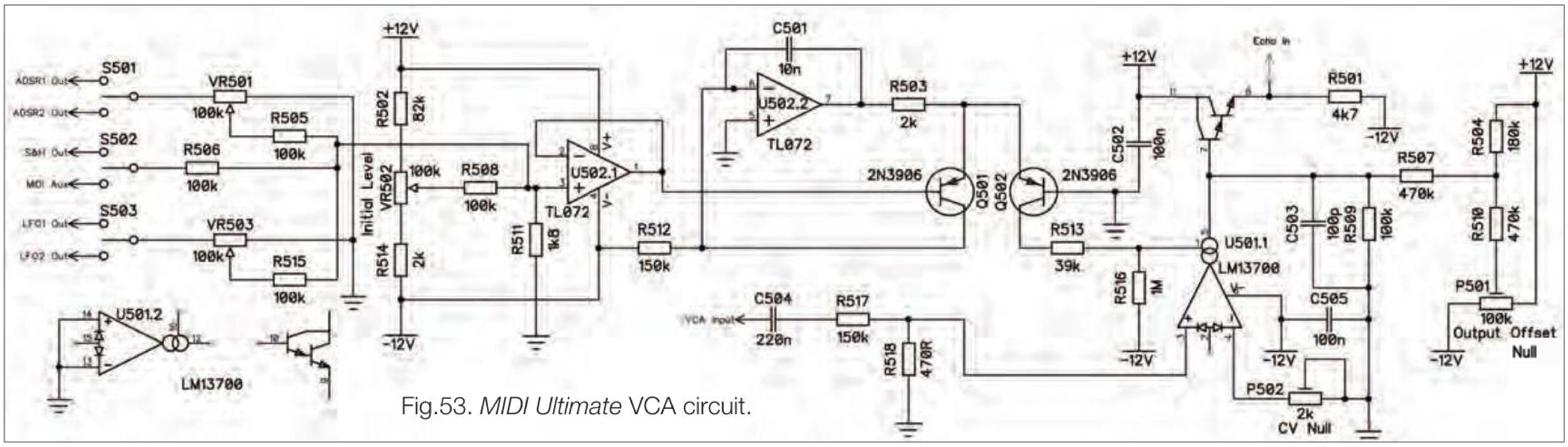
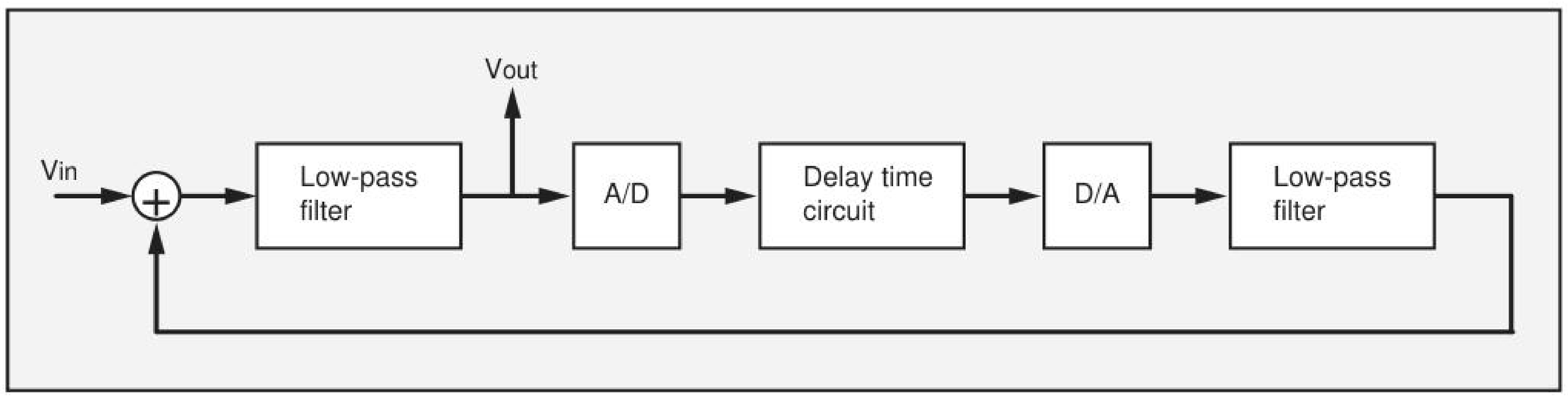

S501
ADSR1 Out
ADSR2 Out
S502
S&H Out
MIDI Aux
S503
LFO1 Out
LFO2 Out
VR501 100k
R505 100k
R506 100k
VR503 100k
R515 100k
+12V
R502 82k
Initial Level VR502 100k
R514 2k
-12V
R508 100k
R511 1k8
U502.1 TL072
R512 150k
C501 10n
U502.2 TL072
R503 2k
2N3906 Q501
Q502 2N3906
R513 39k
R516 1M
VCA input
C504 220n
R517 150k
R518 470R
C502 100n
Echo in
R501 4k7
U501.1 LM13700
C503 100p
R509 100k
C505 100n
R507 470k
R504 180k
R510 470k
P501 100k Output Offset Null
P502 2k CV Null
U501.2
LM13700

Fig.53. *MIDI Ultimate* VCA circuit.


Vin
Low-pass filter
Vout
A/D
Delay time circuit
D/A
Low-pass filter

Block diagram of the internal signal processing of the PT2399.

from the exponential converter is provided to the amp bias input of an LM13700. Since the transconductance through the amp rises with increasing control voltage (converted to current via the exponential convertor) the signal fed to the input grows in amplitude at the output. The current through the LM13700 is converted to voltage by the built-in buffer amplifier (on-board Darlington pair) and fed to the output U501.1 via pin 8.

The VCA will need calibrating for optimum performance, but that will wait until we have the LFOs functioning.

Echo effects

The *MIDI Ultimate* includes an echo-effects module that creates additional harmonics by mixing a delayed output signal with the original.

The circuit is based around the echo processor IC PT2399 from Princeton Technology Corporation, which is widely used in commercial effects products.

The PT2399 (Fig.54) contains an analogue-to-digital converter (ADC), 44kB of sample storage RAM and a digital-to-analogue converter (DAC). The minimum possible delay is 30ms and the maximum is 340ms. Just a few external components for the PT2399 are needed to complete the echo-effects circuit (Fig.55).

The PT2399 is rated to 5V, so voltage regulator U505 has been added to derive the 5V at pin 1 locally from the +12V rail. Three controls are provided:

- VR505, which sets the delay time
- VR506 for the number of repeats (how long the echo continues)
- VR507 for the amount of echo in the output signal.

R528 sets the minimum delay time of around 52ms and VR505 sets the maximum to 280ms with a total harmonic distortion ranging from 0.15% at short delays to 1% at the longest delay.

C528 stabilises the internal reference voltage, and C529 and C527 are used in the modulator/demodulator circuits respectively. C516, C518 and C519 are DC-blocking capacitors on the audio signal lines. C522/R529 and C523/R530 provide low-pass filtering to the input and output summer op amps to reduce noise associated with the sample edges of the ADC. Input and output filtering is provided within the PT2399 defined by the capacitors C524/C525. A proportion of the echo output from pin 12 of U506 is fed via VR506 (length of the echo), C518 and R528. Near maximum settings of the repeats control, pot VR506 will result in a build-up of sounds from continual looping – do try it for yourself!

Headphones amplifier

The *MIDI Ultimate* is a monophonic instrument that would not be pleasing to hear out of just one earpiece of a pair of headphones. The solution is to simply split the audio signal from

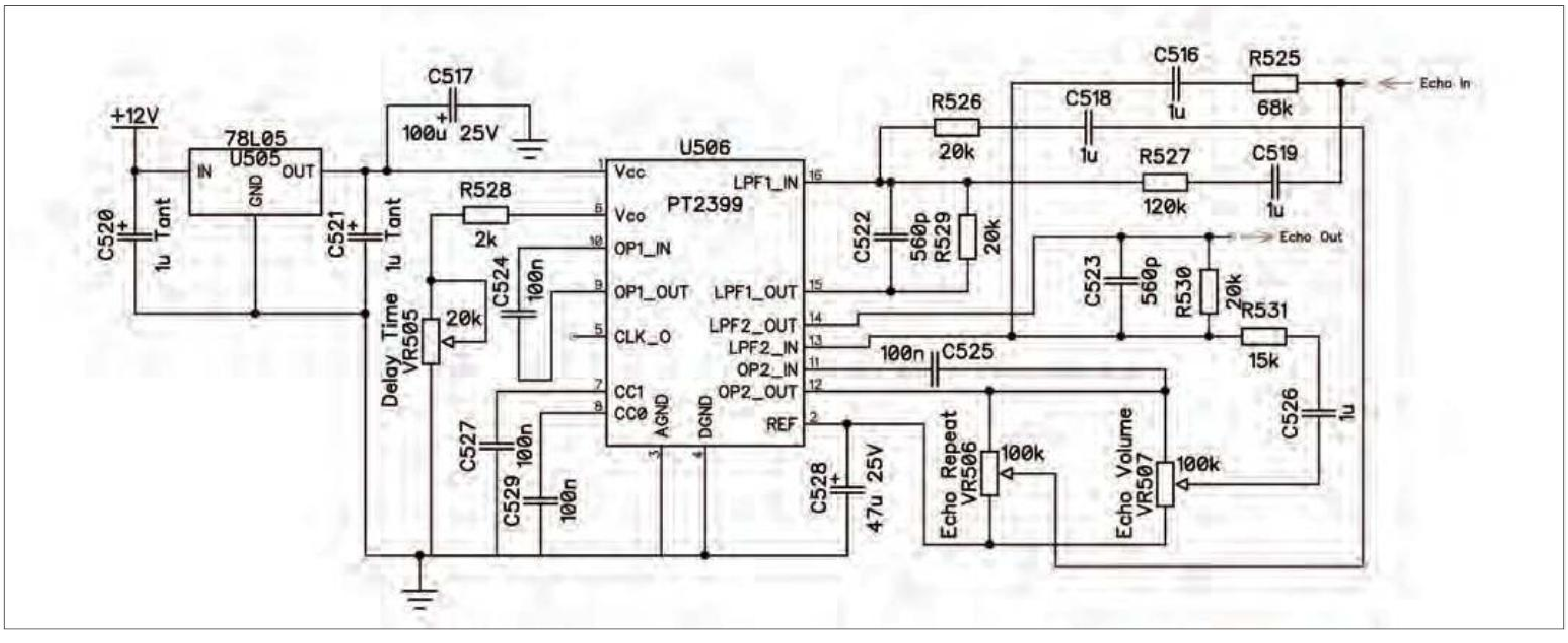

+12V
78L05
U505
IN
OUT
GND
C520 1u Tant
C521 1u Tant
C517 100u 25V
U506
PT2399
Vcc
Vco
OP1_IN
OP1_OUT
CLK_O
CC1
CC0
AGND
DGND
REF
LPF1_IN
LPF1_OUT
LPF2_OUT
LPF2_IN
OP2_IN
OP2_OUT
R528 2k
C524 100n
Delay Time VR505 20k
C527 100n
C529 100n
C528 47u 25V
C522 560p
R529 20k
R526 20k
C518 1u
C516 1u
R525 68k
Echo In
R527 120k
C519 1u
Echo Out
C523 560p
R530 20k
R531 15k
C525 100n
C526 1u
Echo Repeat VR506 100k
Echo Volume VR507 100k

Fig.55. *MIDI Ultimate* echo circuit.

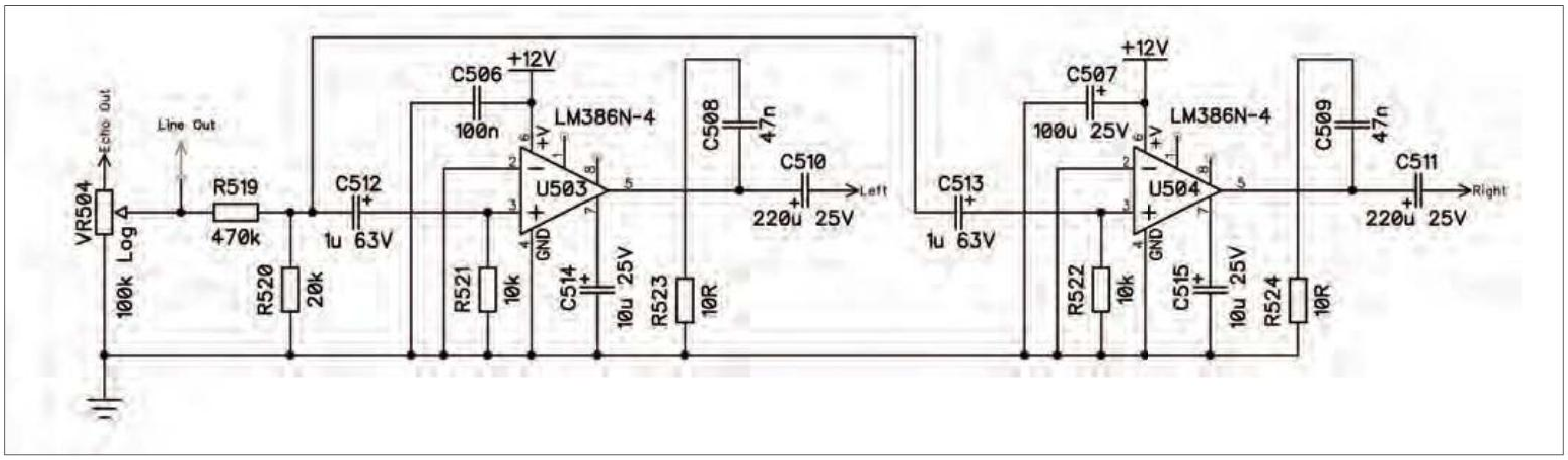

Echo Out
Line Out
VR504
100k Log
R519
470k
R520
20k
C512
1u 63V
C506
100n
+12V
LM386N-4
U503
GND
R521
10k
C514
10u 25V
C508
47n
R523
10R
C510
220u 25V
Left
C513
1u 63V
C507
100u 25V
+12V
LM386N-4
U504
GND
R522
10k
C515
10u 25V
C509
47n
R524
10R
C511
220u 25V
Right

Fig.56. *MIDI Ultimate* stereo headphones amplifier circuit.

the echo circuit to two separate amplifies (Fig.56), one for each of the left- and right-hand channels for the headphones. VR505 is the master level (volume) control and precedes both the mono line output socket and the headphones amplifiers.

Each of the amplifiers is based on the 1W LM386-4 IC. Note the '-4' suffix, which indicates an IC with a higher supply voltage rating than the '-1' and '-3' versions. The circuit is fairly simple, with just a few external components around each of the amplifier ICs. Looking at the left-hand channel, C512 removes any DC from the signal prior to amplification, and C510 after amplification. R519/R520 attenuate the input signal voltage level by around the same amount as the LM386-4 amplifies, thus giving a voltage gain of approximately unity. C514 is a bypass capacitor to help with any power supply noise reduction. The left- and right-hand amplifier outputs connect to the stereo jack socket on the rear panel of the enclosure.

Noise generator

We go to great lengths to keep circuit noise out of our circuits. Circuits with cyclic waveforms such as clock generators, and mains hum or radio interference can propagate unwanted noise through our circuits and appear in the audio signal path. These sources of noise are very unwelcome – but, here is a circuit that deliberately generates noise. Such 'noise generators' are a popular feature of analogue synths because they can be used to produce percussive sounds, or simply wind and sea sound effects. However, not just any old noise will do, we need a noise source that in theory has uniform power across all frequencies. Fig.18 and Fig.19 from *Part 1* show scope traces of the *MIDI Ultimate's* noise source and its spectrum after the low-pass filter. You may well hear noise sources described by a colour: 'white noise' is the 'brightest' sounding. Before the advent of digital TV, you could hear white noise as TV static when no picture transmission was present. 'Pink noise' is 'softer'; noise where the power is attenuated by 3dB/octave. 'Red noise' (also referred to as 'brown' or 'Brownian noise') is softer again – the power is attenuated by 6dB/octave. We can use the VCF to emulate pink and red noise from our white-noise source.

The noise generator circuit in Fig.57 is based around Q1, which is a reverse-biased NPN bipolar transistor (type 2N3904). 12V is connected through R1 to the emitter of Q1, and C2 provides filtering of any power supply noises. The noise signal results from the reverse biasing of the emitter-base junction beyond its emitter-base breakdown voltage level. This results in an avalanche effect in which electrons cascade across the junction, banging into each other and making lots of electrical noise, but at a low voltage level. The noise from Q1 is pre-amplified with a gain of 50 by U1.2, and any DC component is removed by C5. Further amplification is provided by non-inverting amplifier U1.1, whose gain is adjustable by P1 to provide a noise level of ±5V.

It's possible the 2N3904 you use may not generate enough noise. If so, simply swap it out with another one if you cannot get sufficient noise after amplification. It is recommended that you cut the collector leg from Q1 to prevent pickup of noise/EMI (see Fig.45).

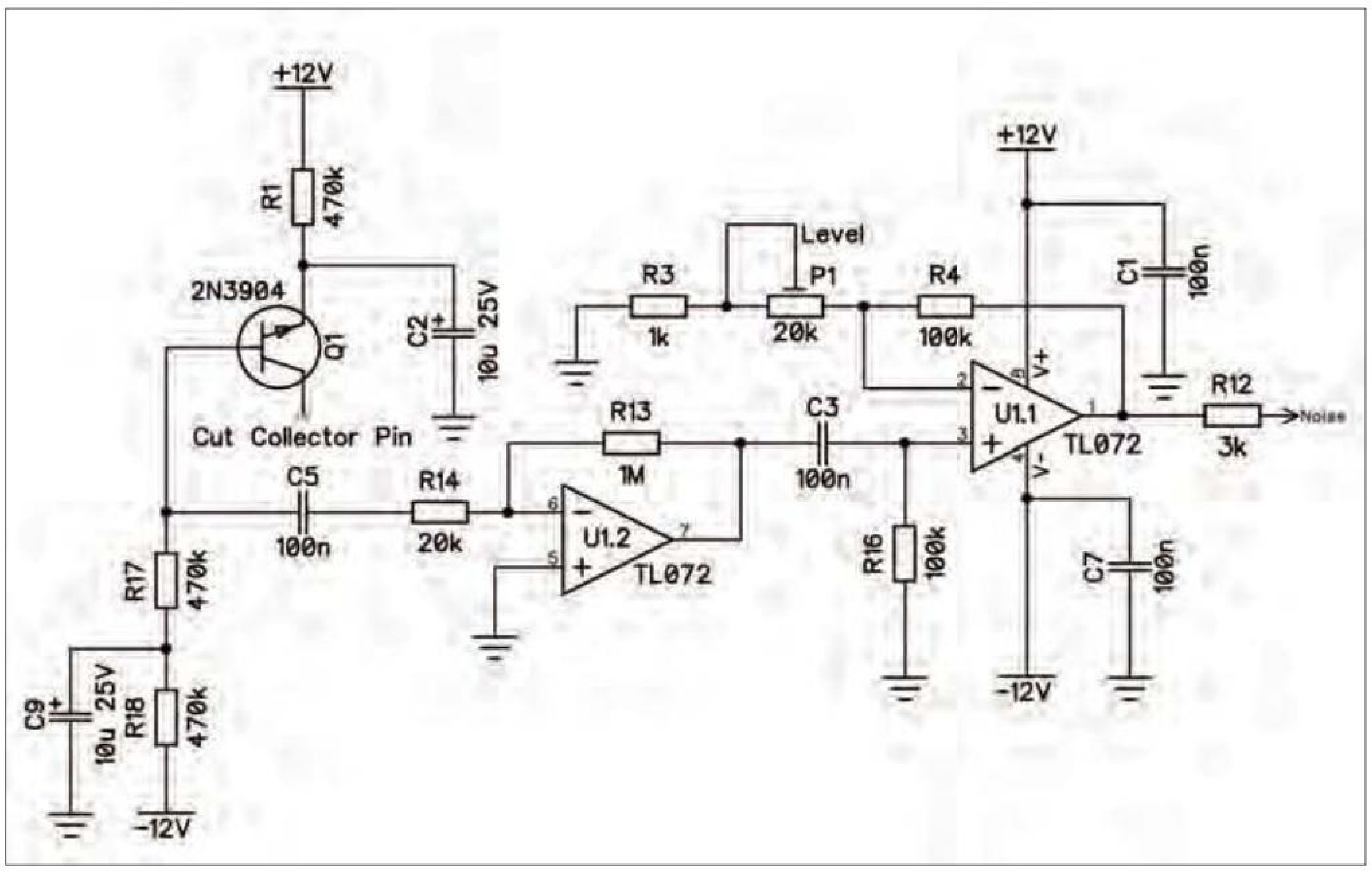

+12V
R1
470k
2N3904
Q1
C2
10u 25V
Cut Collector Pin
C5
100n
R14
20k
R13
1M
U1.2
TL072
R17
470k
C9
10u 25V
R18
470k
-12V
R3
1k
Level
P1
20k
R4
100k
C3
100n
R16
100k
+12V
C1
100n
U1.1
TL072
R12
3k
Noise
C7
100n
-12V

Fig.57. *MIDI Ultimate* white noise generator circuit.

Testing

Prior to applying power, insert the chips for the VCA, noise, echo and amplifiers sections. While there are now ten 25-turn presets, we can leave their adjustment to later – except for P1. You may wish to adjust P1 if you find the noise generator level needs to be louder.

Before we start testing, set the panel controls as follows:

- For each VCO, set the coarse and fine frequency controls and pulse width to mid position (50%). The modulation and PWM modulation fully counter-clockwise (0%)
- Mixer controls all fully counter-clockwise (0%)
- VCF frequency cut-off fully clockwise (100%), resonance fully counter-clockwise (0%)
- VCA initial level fully clockwise (100%)

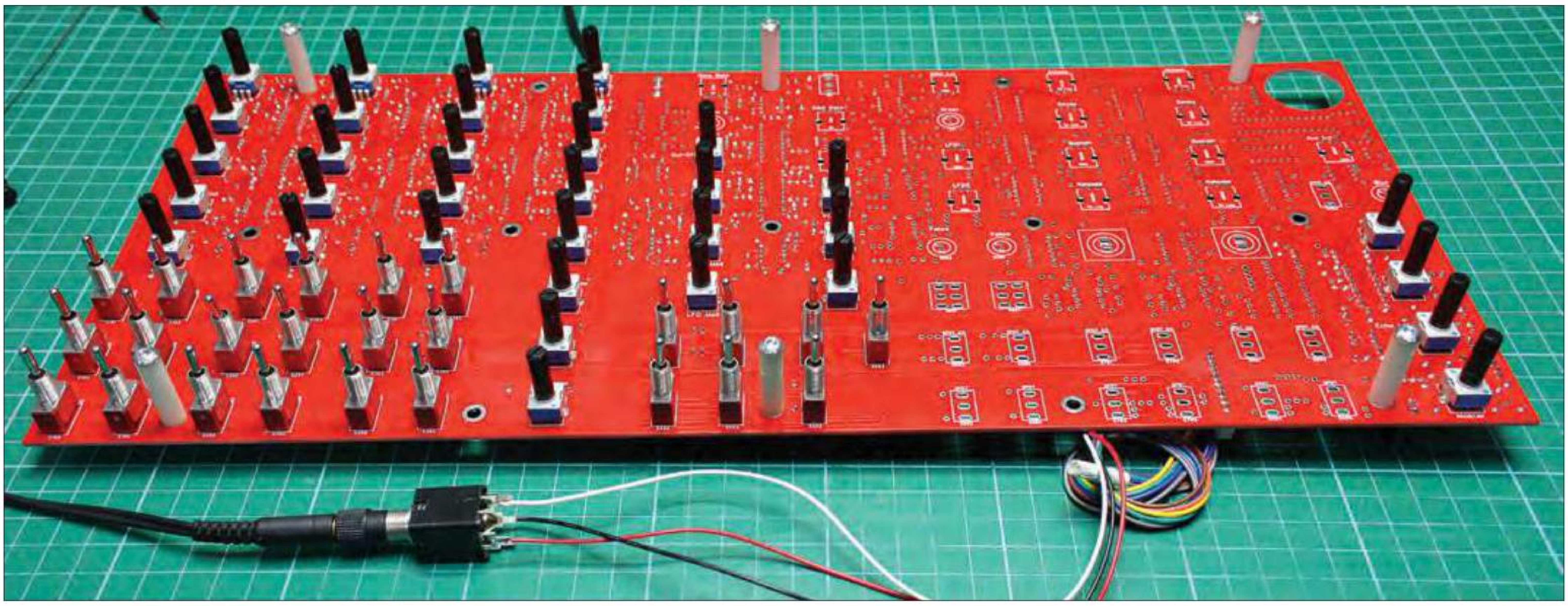


Fig.58. The *MIDI Ultimate* ready for testing the *Part* 3 build stages.

Table 3: Schedule of tests to prove functionality of the headphone amplifier, VCA, echo and noise sections on the PCB

Number	Test	Pots	Result
1	Check audio path including headphone amplifiers	Mixer 'VCO1 sq' to 100% Increase 'Master' level slowly from 0% to until the sound level is comfortable	A square wave tone
2	Check VCA	Reduce VCA initial level from 100% to 0%	The square wave tone will reduce until it can no longer be heard
3	Check echo	VCA initial level 100% VCO1 coarse frequency 0% Echo delay 100%, Echo repeat 75% With your left hand, rapidly turn VCO coarse frequency control back and forth while slowly increasing the echo level pot	Pulses of square wave tones with increasing echoes
4	Check noise generator	Put all pots to the start position Noise pot on mixer to 100%	Sound of white noise. If quiet, adjust preset pot P1 to increase noise level

- All echo controls to fully counter-clockwise (0%)
- Master level fully counter-clockwise (0%)
- All toggle switches to centre off.

Important – check you still have the correct wiring polarity from *Part 2* before applying power. Plug in your headphones or amplifier and power up the synth – all should be silent (Fig.58). The PCB is printed with descriptions for each of the pots to aid identification.

Now perform the tests listed in Table 3.

Test 1 – This is to prove a square wave signal from VCO 1 passes through the mixer, the VCF, the VCA and the echo effect, and can be heard on the headphones. Turning the VCF frequency cut-off control counter-clockwise will reduce the level of harmonics and will sound 'smoother'.

Test 2 – Turning the VCA initial level counter-clockwise will simply reduce the volume of the square wave, the VCA comes into its own when modulated with a control voltage from an ADSR or LFO in *Part 4*.

Test 3 – Echo is best demonstrated with a rapidly changing or intermittent sound. With the VCF cut-off fully clockwise and the VCO 1 coarse frequency control fully counter-clockwise, a very-low-frequency square wave will be produced. By rapidly changing the VCO frequency back and forth (frequency modulation – FM), you will hear the echo increase as you increase the echo level pot.

Test 4 – The last audio signal source to prove is the white noise generator. We will set the average noise voltage level in a later issue, but for now, adjust P1 if it sounds too quiet. You can further experiment by adjusting the VCF cut-off frequency and resonance controls to create pink and red noise.

If you are new to synths, you may be wondering about its potential for producing music. We have seen many DIY synth demo videos that create weird and wonderful sound effects, but we thought we would try something different – actual music compositions! So, to give you a taster, two videos have been published on the Soundtronics Youtube channel. I openly admit to not being a musician I but had great fun learning about the *MIDI Ultimate* and the MIDI recording software. Search Google for 'soundtronics Midi Ultimate youtube' for our YouTube channel.

While there are no modulation sources yet, you can still experiment with the controls you have available and create sound effects.

Note that a term you are likely to come across with synths is a 'patch', which describes the settings and interconnections used to create a particular sound. While the term's origins come from synths where the interconnections were made using plug-in patch leads, it is still used today, even for digitally programmed synths. We will provide some example patches in *Part* 6.

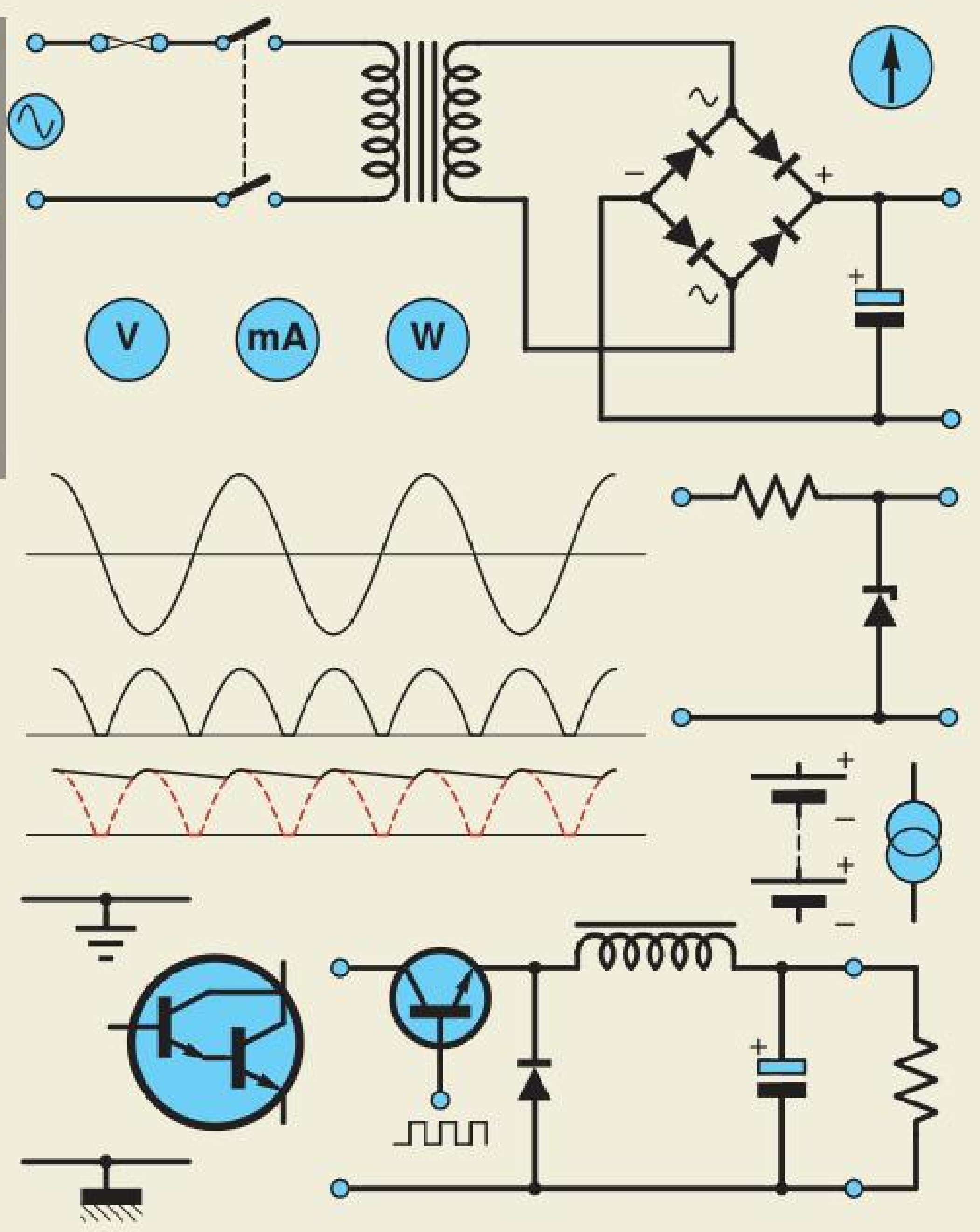
Next month

In *Part 4* next month, we will add the LFO, ADSR, S&H and repeat gate modulation sources. These will really begin to bring the *MIDI Ultimate* to life.

Teach-In 2019

Powering Electronics

Part 5: SMPS controllers



by Mike Tooley

Your project is finished and ready to go, but the job isn't done until you've found an appropriate source of power. This could be as simple as choosing a suitably rated mains adapter or as complex as designing a switched-mode power supply with multiple outputs and battery backup. Our latest series – *Teach-In 2019* – is here to help, and will provide you with insight into all aspects of powering your electronic projects and designs.

Last month, we introduced switched-mode power supplies (SMPS) and explained the basic principles of buck (step-down) and boost (step-up) switching regulators. This month, we will be taking a detailed look and exploring the controller chips used in most of today's switched-mode supplies.

These versatile devices offer a neat solution to the problem of controlling and regulating the output of an SMPS. Our *Practical Project* takes the form of an efficient SMPS regulator. So that you can explore the operation of the circuit at individual component level we have based the design on a handful of discrete components rather than a dedicated SMPS controller.

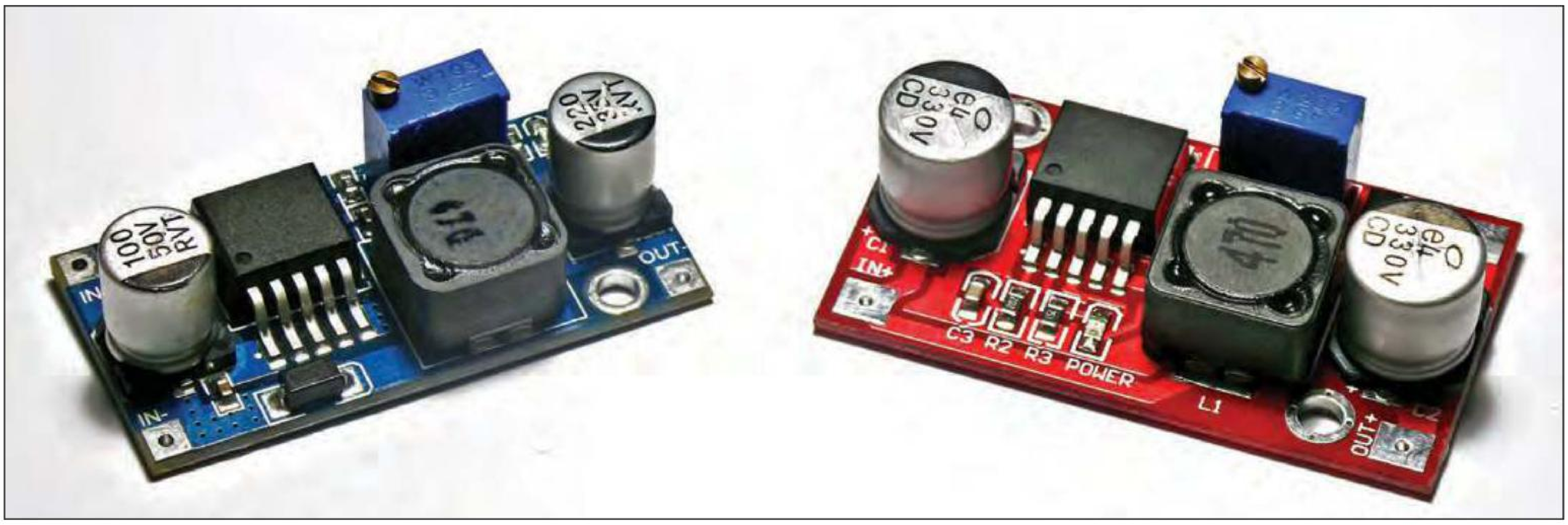


Fig.5.1. Inexpensive buck (L) and boost (R) regulators are available from component retailers and on-line sources.

SMPS controller chips

A wide range of dedicated SMPS controller chips is available, and this can greatly simplify the task of designing and building a power supply based on switched-mode technology. As well as improving reliability and performance, the use of a dedicated controller chip can significantly reduce component count and circuit board size; also, ready-made switched-mode regulators are available at bargain prices from several component retailers and on-line sources (see Fig. 5.1).

SMPS controllers usually combine the function of a converter (with or without

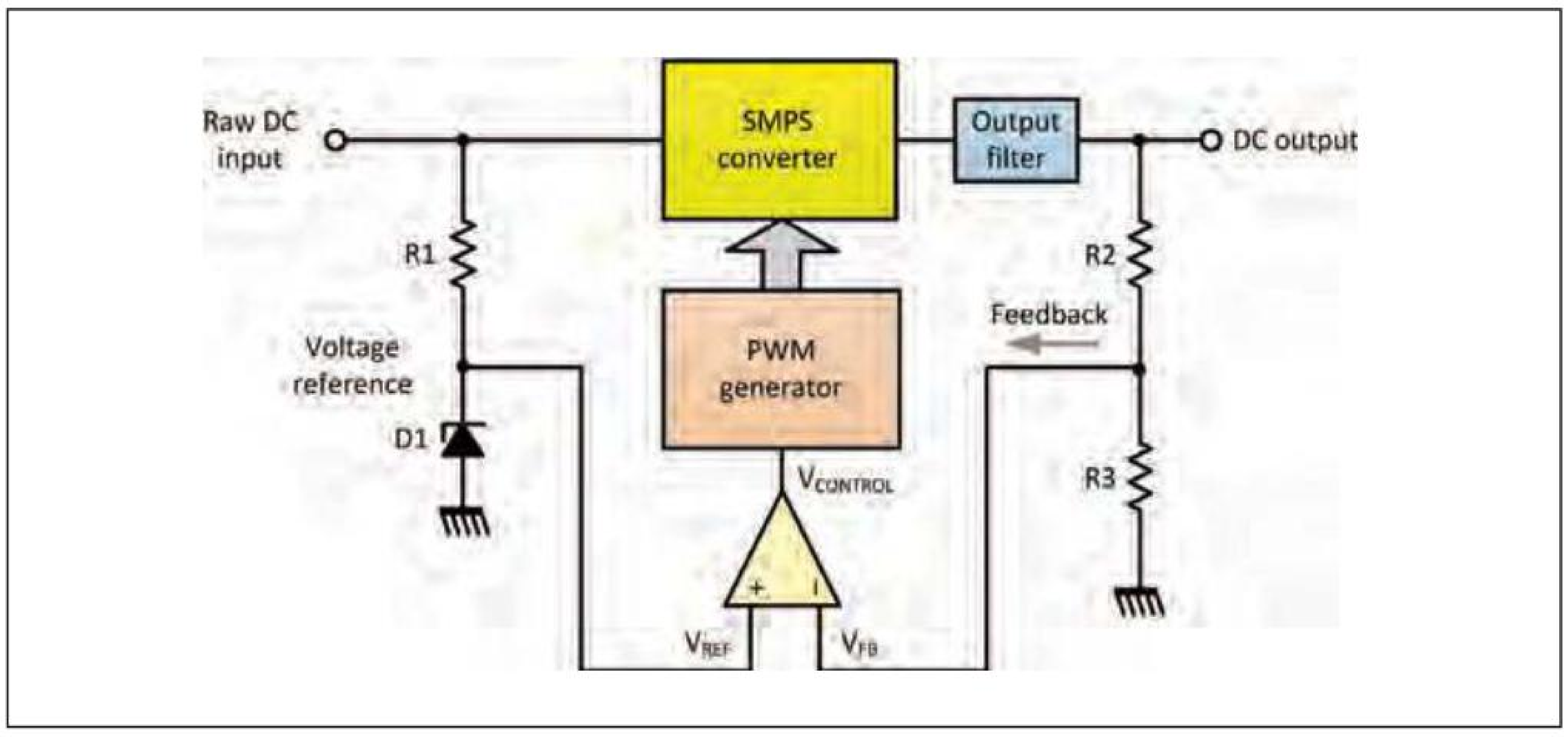


Fig.5.2. Simplified arrangement of an SMPS controller combining the functions of converter and regulator.

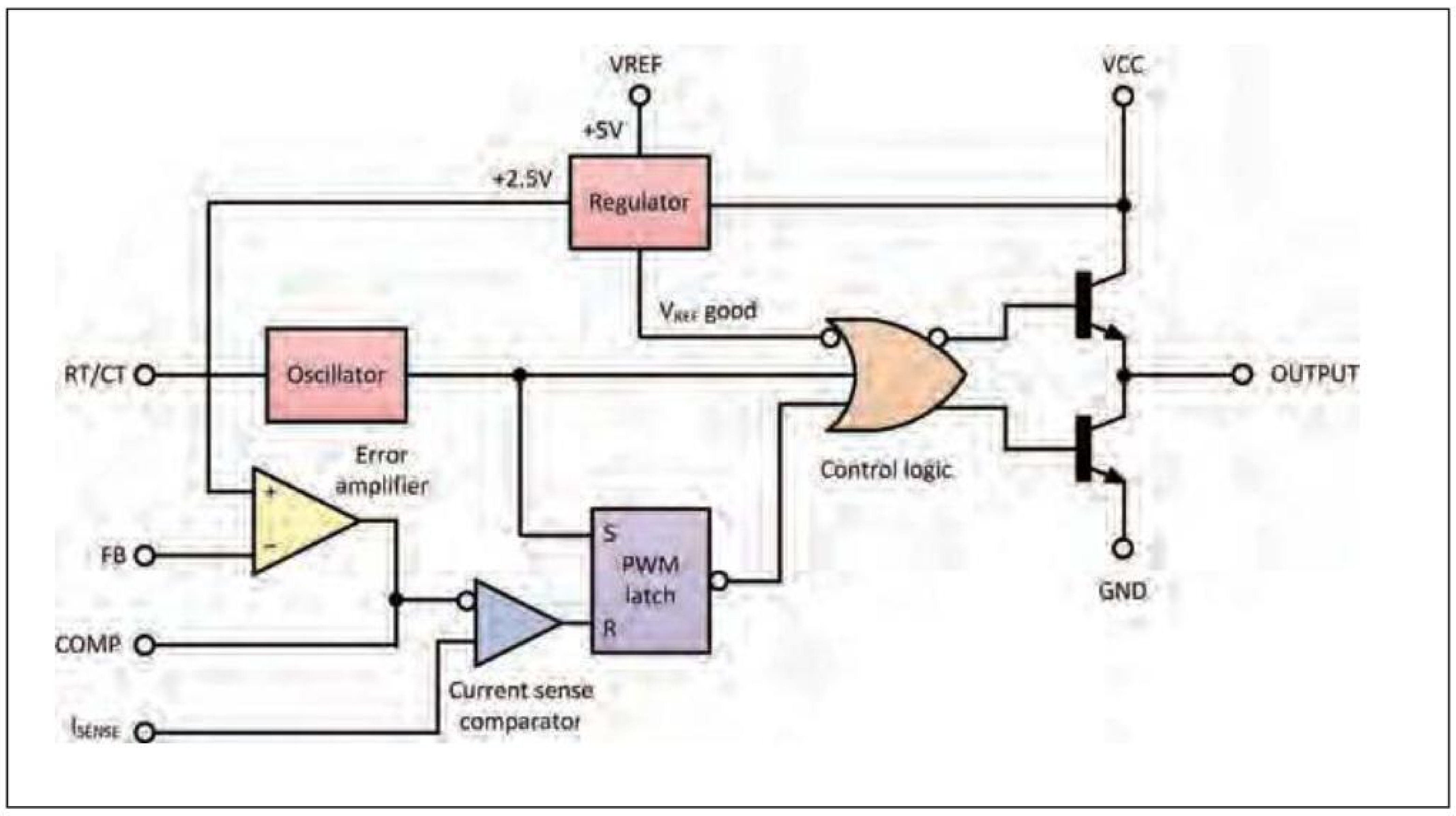

VREF
+5V
VCC
+2.5V
Regulator
V_{REF} good
RT/CT
Oscillator
OUTPUT
Error amplifier
Control logic
FB
S
PWM latch
R
GND
COMP
Current sense comparator
I_{SENSE}

Fig.5.3. Simplified internal architecture of the UC3842 SMPS controller.

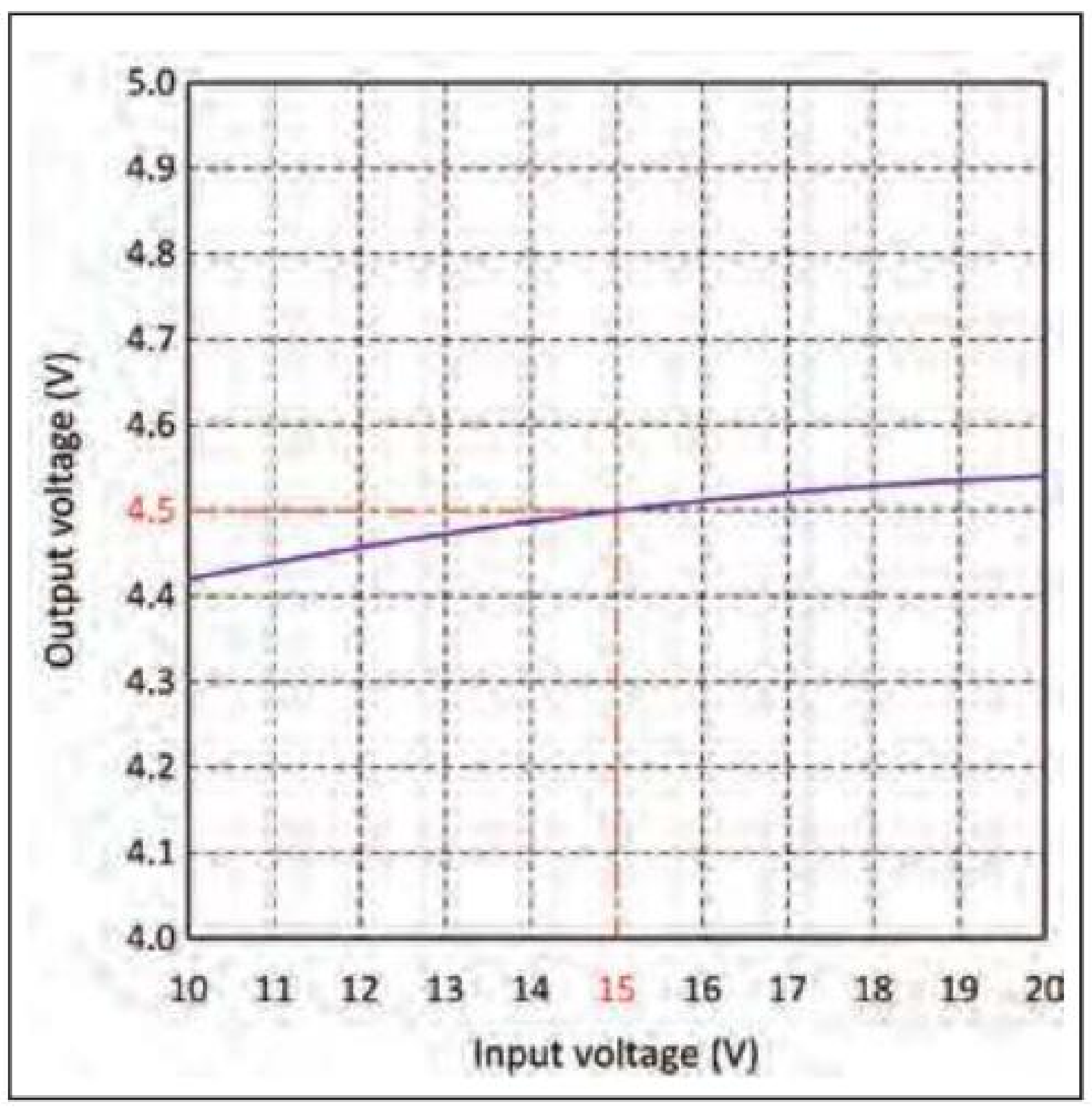


Fig.5.5. Line regulation characteristic for the circuit of Fig.5.4.

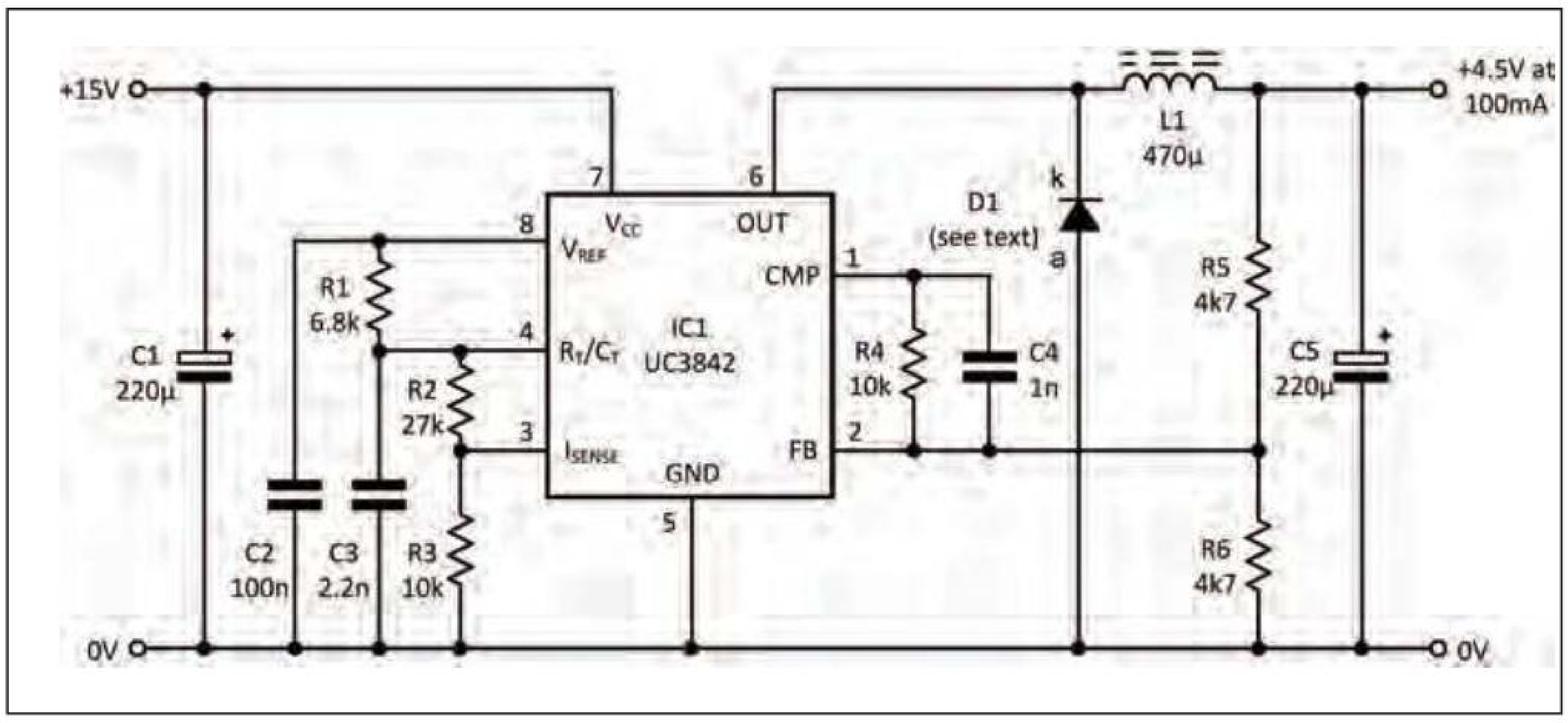

+15V
+4.5V at 100mA
L1 470µ
7
6
8
V_{CC}
OUT
D1 (see text)
k
a
V_{REF}
1
CMP
R1 6.8k
4
R_T/C_T
IC1 UC3842
R5 4k7
C1 220µ
R2 27k
R4 10k
C4 1n
C5 220µ
3
I_{SENSE}
FB
2
GND
5
C2 100n
C3 2.2n
R3 10k
R6 4k7
0V
0V

Fig.5.4. A buck regulator based on a UC3842 SMPS controller. The circuit delivers 4.5V at 100mA from a nominal DC input of 15V.

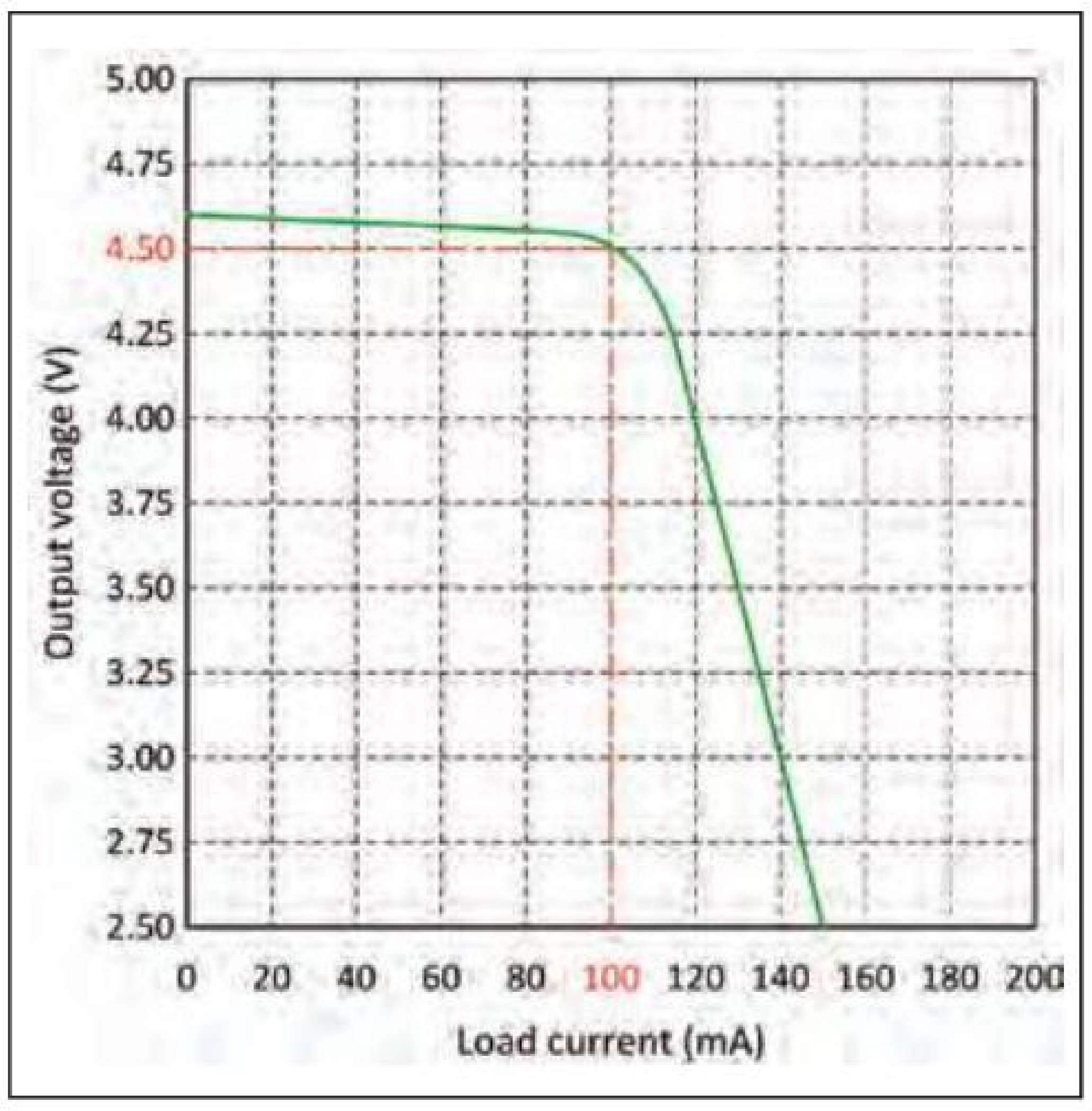


Fig.5.6. Load regulation characteristic for the circuit of Fig.5.4.

an external power switching device) with that of a regulator and switching source based on a pulse-width modulated (PWM) oscillator working with an error amplifier and voltage reference. Other features, such as an internal voltage reference, current sensing and limiting, soft-start and standby power control can also be incorporated in controller chips.

The UCx84x family of controllers manufactured by Texas Instruments provides the necessary features to control an SMPS. The simplified internal architecture of the UC3842 is shown in Fig.5.2. Fig.5.3 shows how the Texas Instruments UC3842 SMPS controller chip can be used in a simple buck regulator that produces an output of 4.5V at 100mA without the need for an external switching transistor.

Fig.5.4 shows a buck regulator based on the UC3842. This device operates from a supply current of just 11mA, but has a very much greater output drive capability. Note that the output of the UC3842 is often fitted with additional Schottky diodes (not shown in Fig5.4) to prevent the chip's substrate becoming negatively biased. Other family members (such as the UCC3802 and UCC3809) have low-current CMOS outputs and therefore don't require this precaution. The device operates with switching frequencies of up to 500kHz and the internal oscillator frequency is set by means of a single resistor and capacitor (R2 and C3 in Fig.5.4).

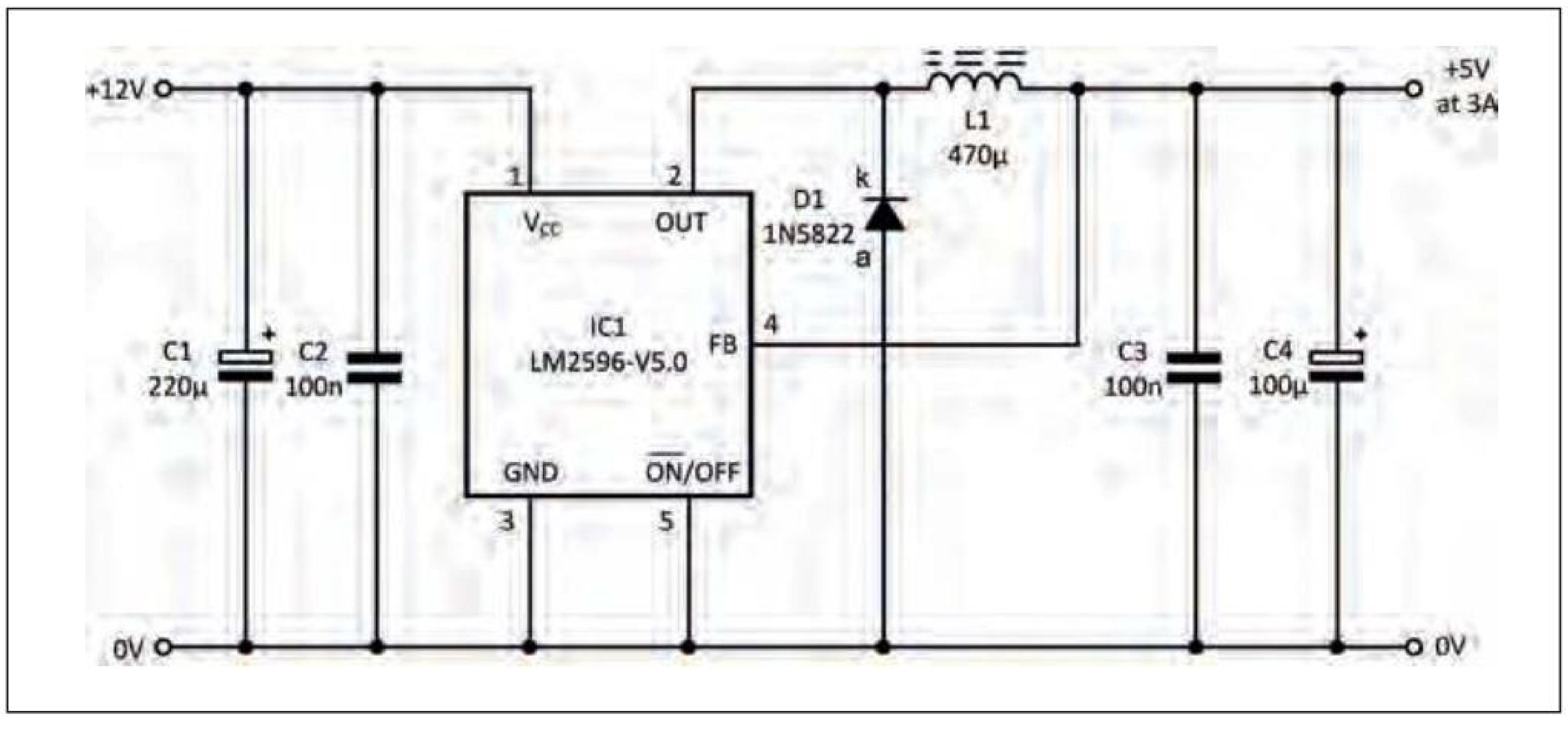

+12V
+5V at 3A
L1 470µ
1
2
V_{CC}
OUT
D1 1N5822
k
a
C1 220µ
C2 100n
IC1 LM2596-V5.0
FB
4
C3 100n
C4 100µ
GND
$\overline{ON}$/OFF
3
5
0V
0V

Fig.5.7. A buck regulator based on an LM2596-V5.0. The circuit delivers a fixed output of +5V at 3A and can make an excellent replacement of a fixed three-terminal linear voltage regulator.

The circuit was designed to replace a somewhat inefficient low-voltage supply based on a 4.7V shunt Zener diode. The circuit delivers 4.5V at 100mA from a nominal DC input of 15V and operates with an efficiency approaching 90%, whereas the linear-mode shunt regulator which it replaced only manages 30%, or so. The line and load regulation characteristics for the circuit of Fig.5.4 are shown respectively in Figs.5.5 and 5.6.

The LM2596 SMPS controller

The Texas Instruments LM2596HV series of regulators are monolithic integrated circuits that also provide a full range of functions for use in a wide variety of SMPS applications. These devices are available in fixed output voltages of 3.3V, 5V, 12V and also in an adjustable output version. The chips are available in a standard 5-lead TO-220 package, and also 5-lead TO-263 surface-mount and SOP-8 packages. For most home construction projects, we recommend the 5-lead TO-220 version because this package is much easier to handle.

The LM2596 incorporates an external shutdown feature with a very economical 30µA standby current. The output switch includes cycle-by-cycle current limiting, as well as thermal shutdown. Last, but not least, the LM2596 controller makes possible an easy-to-build yet fully functional SMPS using only four external components!

Fig.5.7 shows a very simple buck regulator based on an LM2596-V5.0. The circuit delivers a fixed output of +5V at 3A and can make an excellent and highly efficient replacement for a fixed three-terminal linear voltage regulator such as a 7805 (see *EPE*, February 2019, page 37).

Practical wiring and layout considerations

The wiring and PCB layout of a switched-mode power supply is far more critical than that of most linear power supplies. The penalty for not paying close attention to circuit layout can result in significant amounts of noise being radiated from a circuit board and its associated wiring, as well as conducted along interconnecting leads and cables. This high-frequency noise is a product of the fast switching action of the SMPS, but it can be greatly reduced by carefully positioning decoupling capacitors (C1 to C4 in Fig.5.7) in close proximity to the SMPS controller and other switching device. It is also essential to ensure a very short, direct and low resistance path to the circuit's ground connection. Fig.5.8 illustrates this important point.

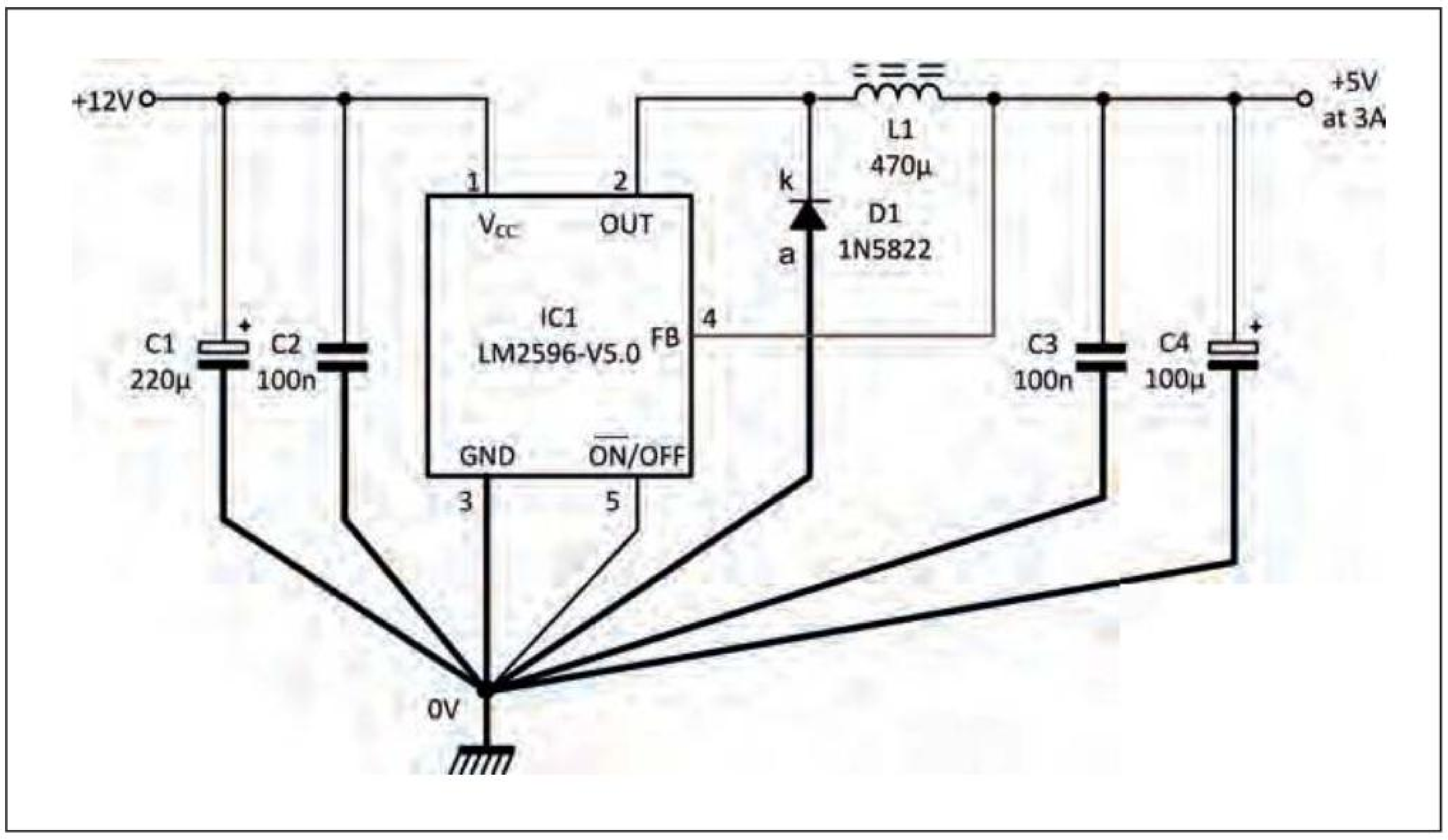


Fig.5.8. Practical wiring considerations for the circuit shown in Fig.5.7. To avoid noise and instability, the heavy lines should be kept as short as possible and should use wide PCB tracks. A single common/0V (ground) connection should be used for both input and output and the feedback wiring (shown in red) should be routed well away from the inductive component (L1).

Using off-the-shelf SMPS modules

At this point it is important to mention that off-the-shelf SMPS modules are becoming widely available at very moderate cost and it is well worth investigating a ready-built module rather than attempting to design and construct an SMPS from scratch. Fig.5.9 shows the circuit of a complete 3.3V 3A SMPS regulator based on the variable output version of the LM2596 chip. The PCB-mounted version of this circuit (see Fig.5.10) is readily available at low cost from several retailers and on-line sources (search for 'LM2596 module' at eBay, Banggood and GearBest). Do shop carefully – there are several variants, so make sure you buy what you need.

The performance of the circuit in Fig.5.9 is outstanding and can be gauged from the load regulation characteristic shown in Fig.5.11. This graph clearly shows how the SMPS regulator's output voltage (3.3V) remains substantially constant over the full range of load currents up to the rated maximum output of 3A.

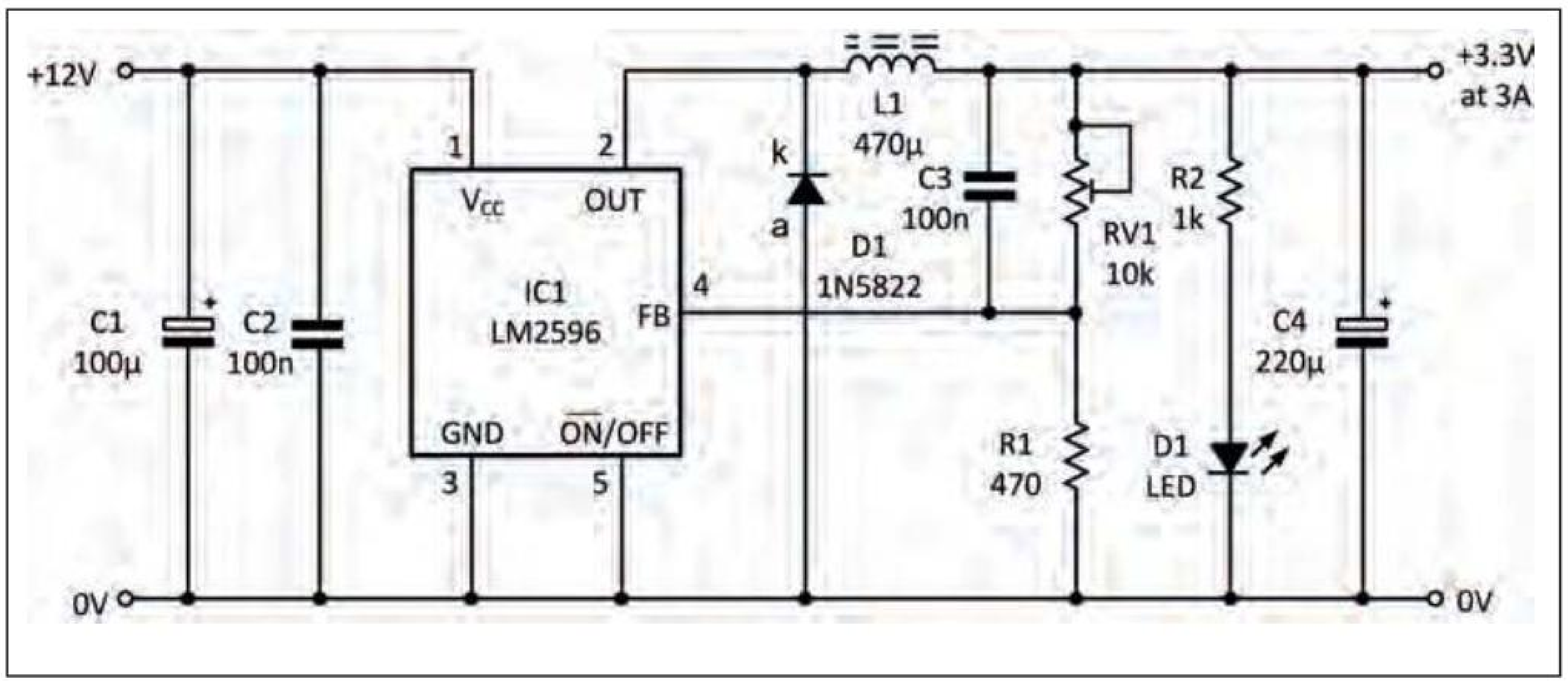


Fig.5.9. A complete 3.3V 3A SMPS regulator based on the variable output version of the LM2596 chip.

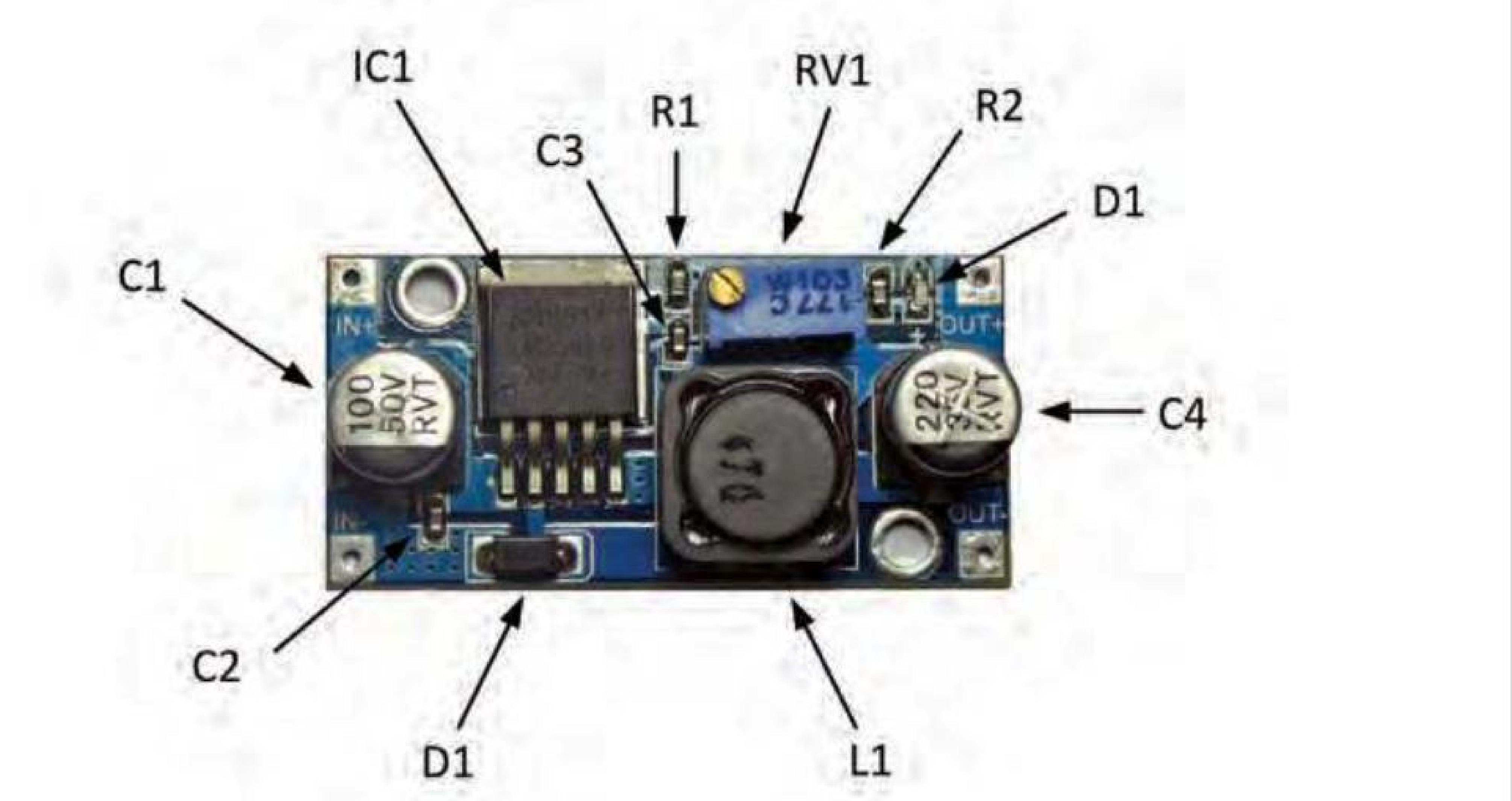


Fig.5.10. A low-cost off-the-shelf buck regulator based on the circuit shown in Fig.5.9.

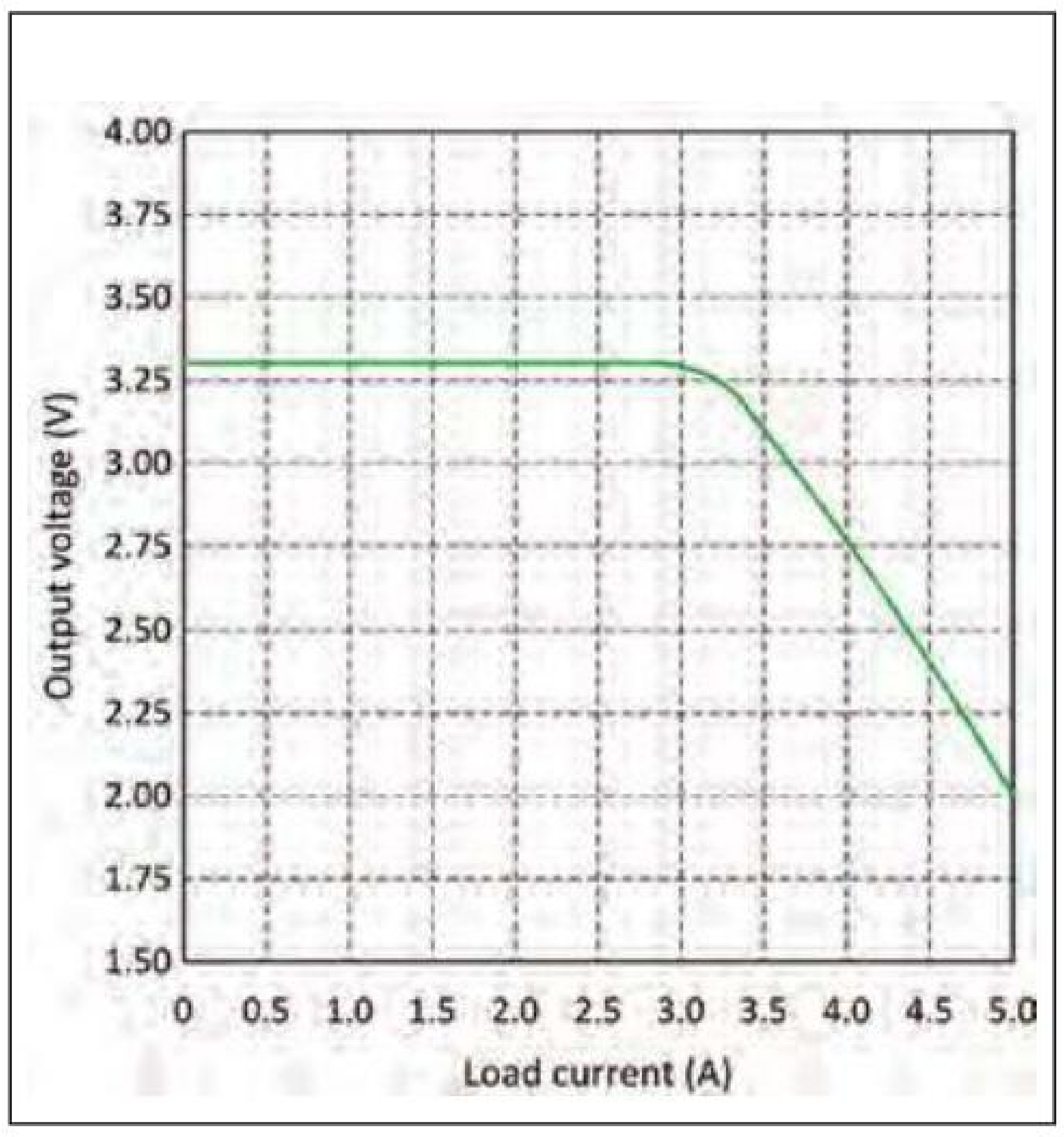


Fig.5.11. Load regulation characteristic for the buck regulator shown in Fig.5.9.

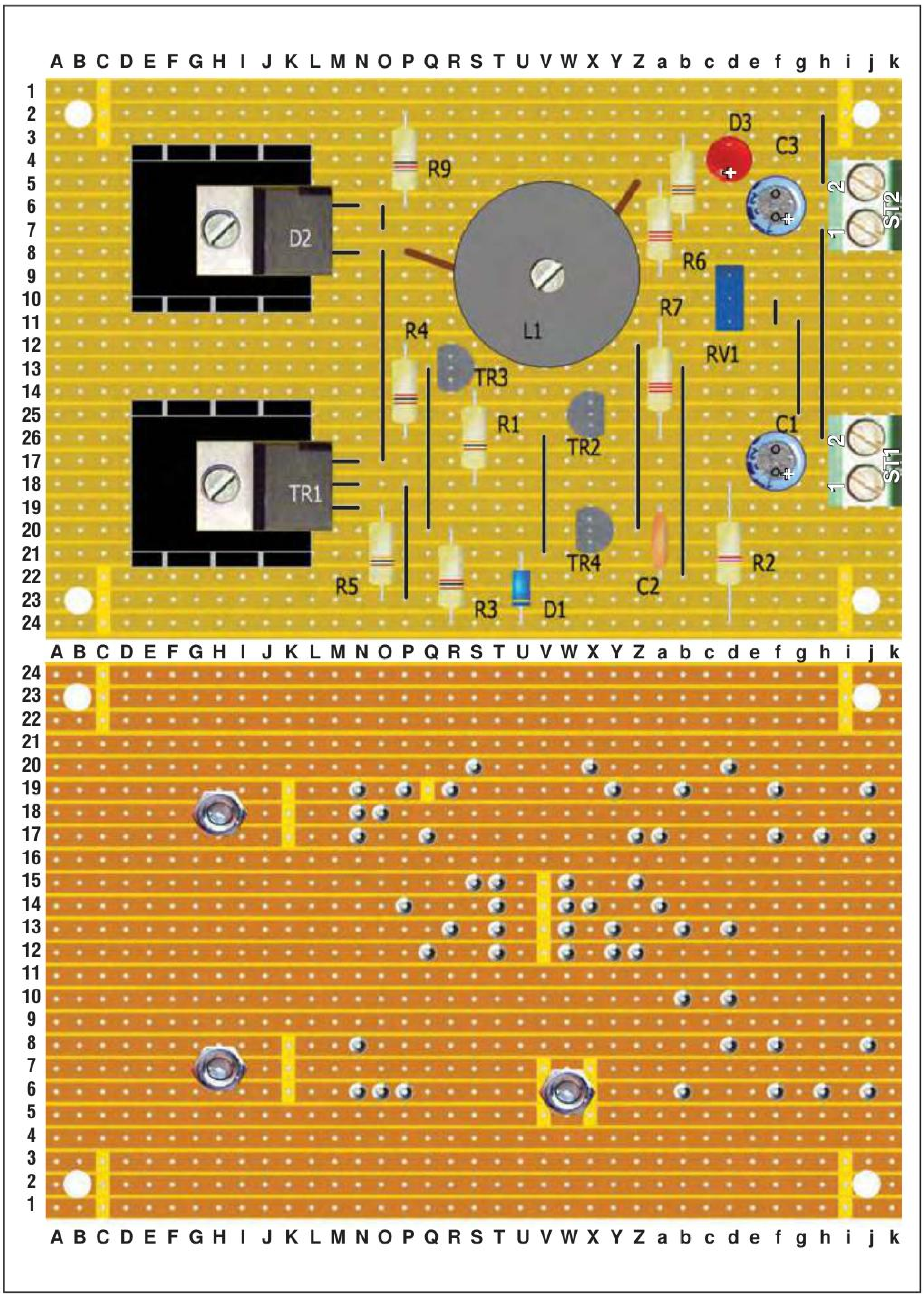
Practical Project: SMPS regulator

This month's *Practical Project* takes the form of an SMPS regulator based on discrete component technology. The use of individual components will allow you to investigate voltages and waveforms within the circuit and also allows you to make changes to component values which would be impossible inside an SMPS controller chip. The circuit has been kept as simple as possible and uses just four transistors and three diodes.

The SMPS regulator is designed to produce a fixed output voltage of 6V at load currents up to 2A. The circuit incorporates a pre-set adjustment so that the output can be typically set between 5.6V and 6.8V. The circuit is ideal for supplying power to small microcontrollers (eg, Arduino or Raspberry Pi) from a vehicle battery or from an unregulated 12V DC mains adapter. The circuit's specifications are as follows:

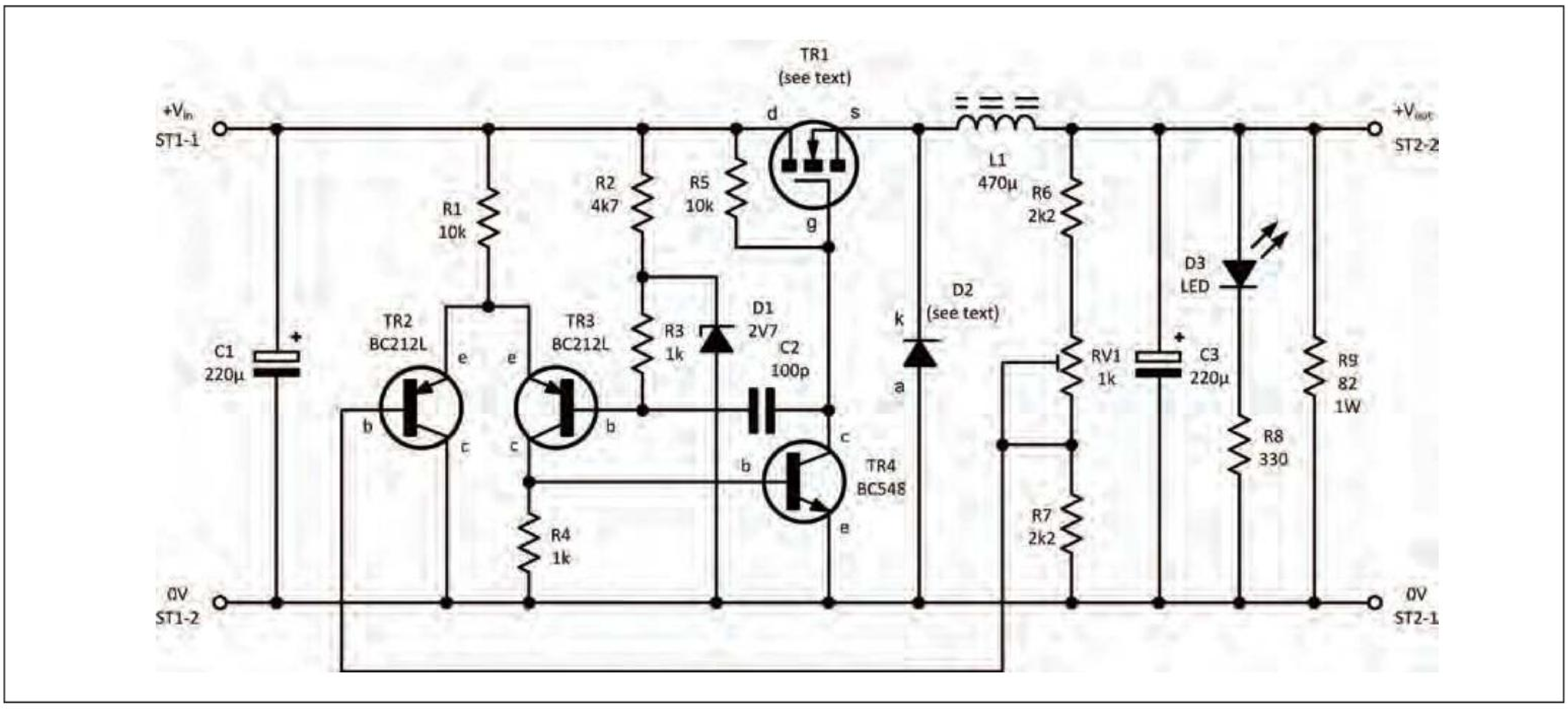
Input voltage	10V to 15V
Output voltage	6V
Adjustment range	5.6V – 6.8V approx
Load current	2A max.
Switching freq	45kHz approx
Noise	<50mV pk-pk at 1A output
Line regulation	6%
Load regulation	better than 4%
Output resistance	0.125Ω

The circuit of our SMPS regulator is shown in Fig.5.12. The differential arrangement formed by TR2 and TR3 acts as a simple error amplifier with feedback voltage derived from the potential divider consisting of R6, RV1 and R7. The output of the error amplifier is derived from the collector of TR3 and applied to TR4, which drives the gate of the power switching MOSFET, TR1.



A B C D E F G H I J K L M N O P Q R S T U V W X Y Z a b c d e f g h i j k
1 2 3 4 5 6 7 8 9 10 11 12 13 14 25 26 17 18 19 20 21 22 23 24
D3
C3
R9
D2
R6
L1
R7
RV1
R4
TR3
R1
TR2
C1
TR1
ST2
ST1
1
2
TR4
R2
R5
C2
R3
D1
24 23 22 21 20 19 18 17 16 15 14 13 12 11 10 9 8 7 6 5 4 3 2 1

Fig.5.13. Stripboard layout of the SMPS regulator.



TR1
(see text)
d
s
g
+V$_{in}$
ST1-1
L1
470µ
+V$_{out}$
ST2-2
R1
10k
R2
4k7
R5
10k
R6
2k2
D3
LED
D2
(see text)
k
a
TR2
BC212L
TR3
BC212L
R3
1k
D1
2V7
C2
100p
C1
220µ
RV1
1k
C3
220µ
R9
82
1W
R8
330
b
e
c
TR4
BC548
R4
1k
R7
2k2
0V
ST1-2
0V
ST2-1

Fig.5.12. This month's Practical Project is an SMPS regulator based on discrete components.

To provide the switching pulses, TR3 and TR4 form an astable oscillator with positive feedback via C2, which sets the switching frequency (approximately 45kHz). The square wave pulse waveform appearing at the drain of TR2 is rectified by means of fast-switching diode D1, and the positive output voltage is developed across C3, which acts as a reservoir capacitor. LED D2 and its associated current-limiting series resistor (R8) indicate the presence of the DC output voltage.

You will need...

Perforated copper stripboard (24 strips each with 37 holes)
2 2-way PCB screw terminal connectors (ST1, ST2)
2 10Ω resistors (R1, R5)
2 1kΩ resistors (R3, R4)
1 4.7kΩ resistor (R2)
2 2.2kΩ resistors (R6, R7)
1 330Ω resistor (R8)
1 89Ω 1W resistor (R9)
1 1kΩ miniature pre-set resistor (RV1)
2 220μF 35V capacitors (C1, C3)
1 100pF ceramic capacitor (C2)
1 470μH ferrite cored inductor (see text)
1 RFP30N06LE (TR1) (see text)
2 BC212L NPN transistors (TR2, TR3)
1 BC548 NPN transistor (TR4)
1 BYW29 (D1) (see text)
1 2.7V Zener diode
1 red LED (D3)
2 small TO220 heatsinks (see text)
4 stand-off pillars and mounting screws

Construction

The stripboard layout of the SMPS regulator is shown in Fig.5.13. Note that there are 29 track breaks on the underside of the board and 11 links on the upper side. The pin connections for the semiconductor devices are shown in Fig.5.14. The two TO-220 heatsinks should be rated at 9.1°C/W, or better. Furthermore, to improve heat dissipation the two power semiconductor devices (TR1 and D1) are mounted directly on their respective heatsinks. These must not be allowed to make contact with the enclosure or any other component parts.

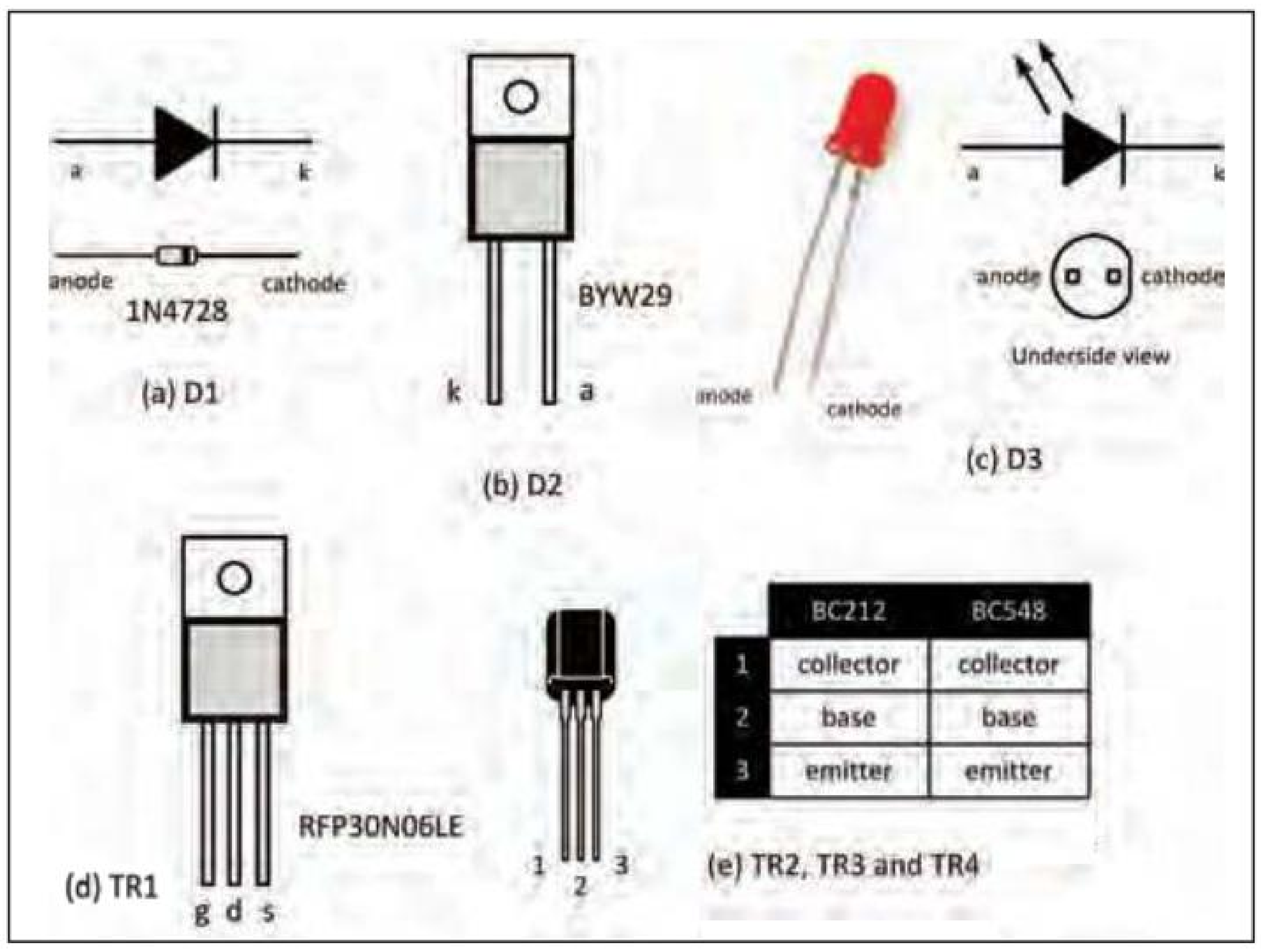


Fig.5.14. Device connections for the SMPS regulator.

As always, once the assembly is complete it is well worth carrying out a careful inspection of the circuit board, particularly checking the off-board wiring and links to connectors ST1 and ST2.

We have used very conservatively rated devices for TR1 and D1. Both of these components are reasonably common but many similar semiconductor devices are available and can be used instead. For example, TR1 could be any suitably rated N-channel MOSFET switching transistor with a maximum voltage rating of greater than 50V and an 'on' resistance of less than 0.1Ω. (Note that the drain connection of this device is connected directly to the mounting tab and therefore it will be at the same potential as the heatsink when no insulating washers are fitted).

The switching diode (D1) is an ultrafast rectifier designed specifically for use in a wide range of SMPS designs, but any similar device can be used provided that it is rated for a current of at least 5A and a voltage of greater than 50V. Finally, the ferrite-cored inductor used in the switched-mode boost converter must be rated at 2A and have a DC resistance of less than 0.3Ω. A suitable component is available from Murata Power Solutions (part number 1447423C – sold by **mouser.co.uk** as part number 580-1447423C). We will be discussing ferrite components in a later *Teach-In 2019*.

Fig.5.16 and Fig.5.17 show the line and load regulation characteristics for the SMPS regulator respectively. Note that the minimum and maximum recommended input voltages are 10V and 15V respectively, and that the output voltage is 6V on no load and falls to 5.75V on full load. If you need to maintain 6V at full load it will be necessary to adjust RV1 accordingly (in which case the no-load output voltage will rise to around 6.25V).

Next month

In *Part 6* of *Teach-In 2019* next month, we will introduce voltage multipliers and our *Practical Project* will be a simple low-current 9V-to-15V supply converter.

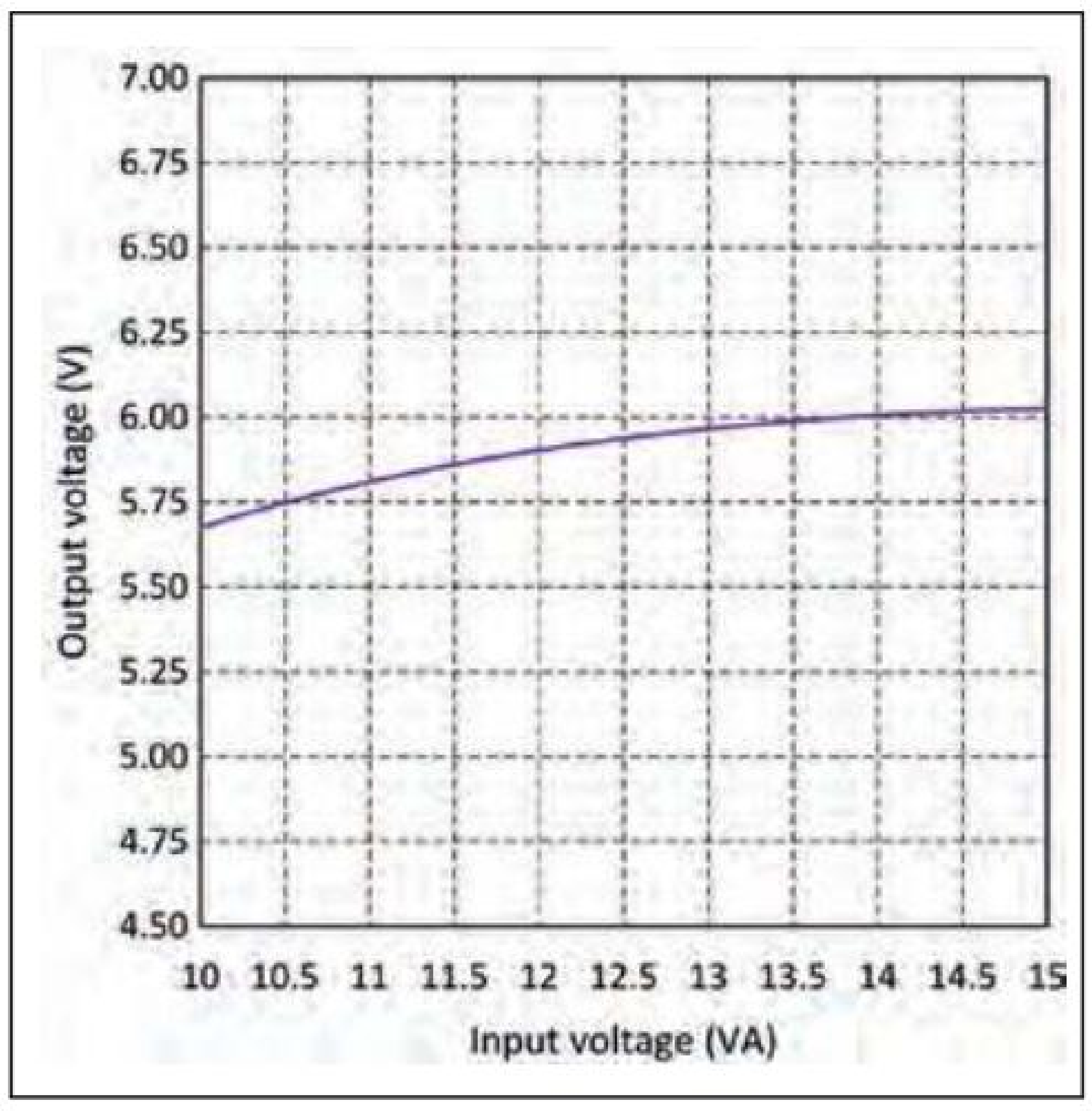


Fig.5.16. Line regulation characteristic for the SMPS regulator.

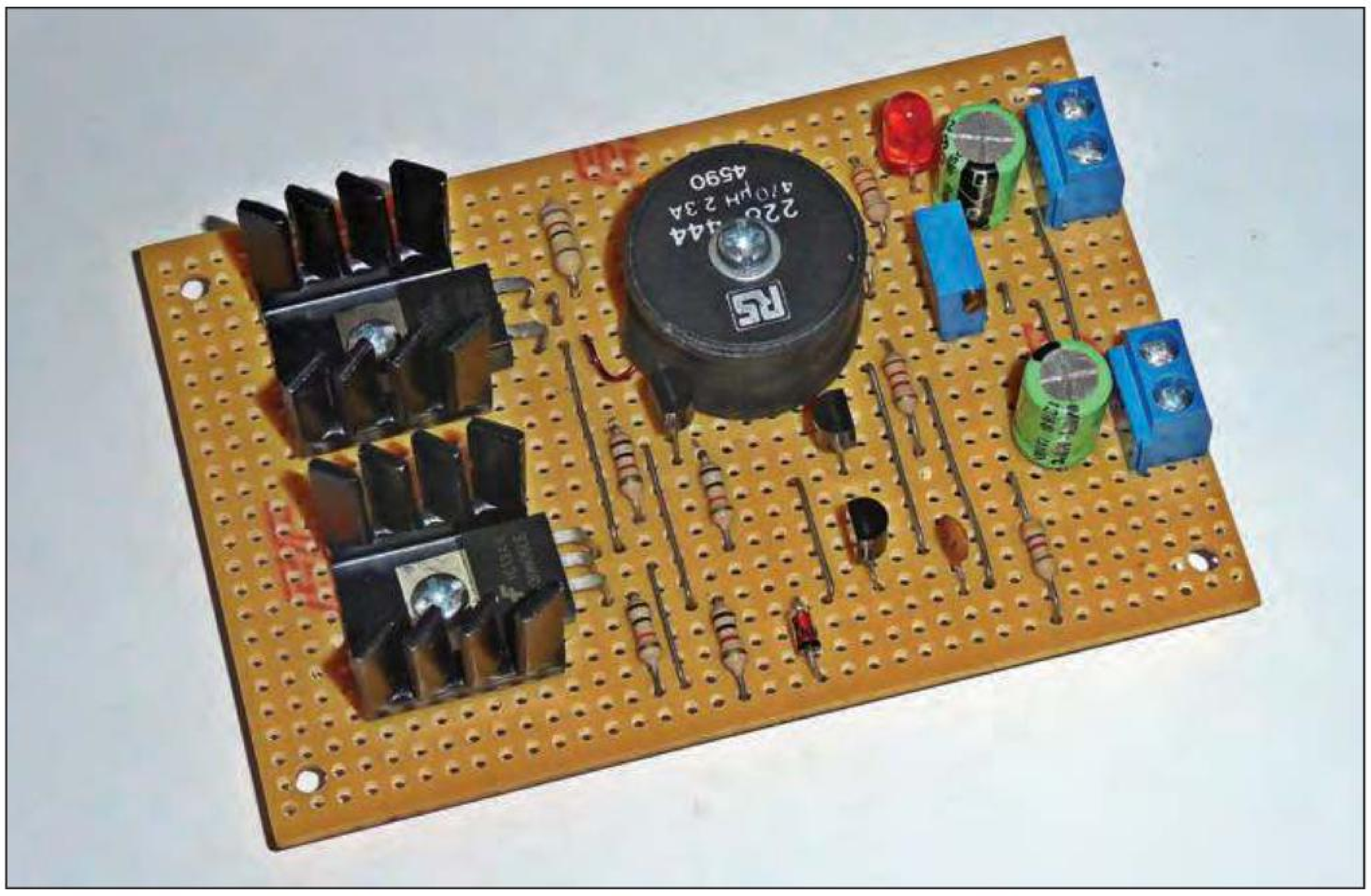


Fig.5.15. The finished SMPS regulator.

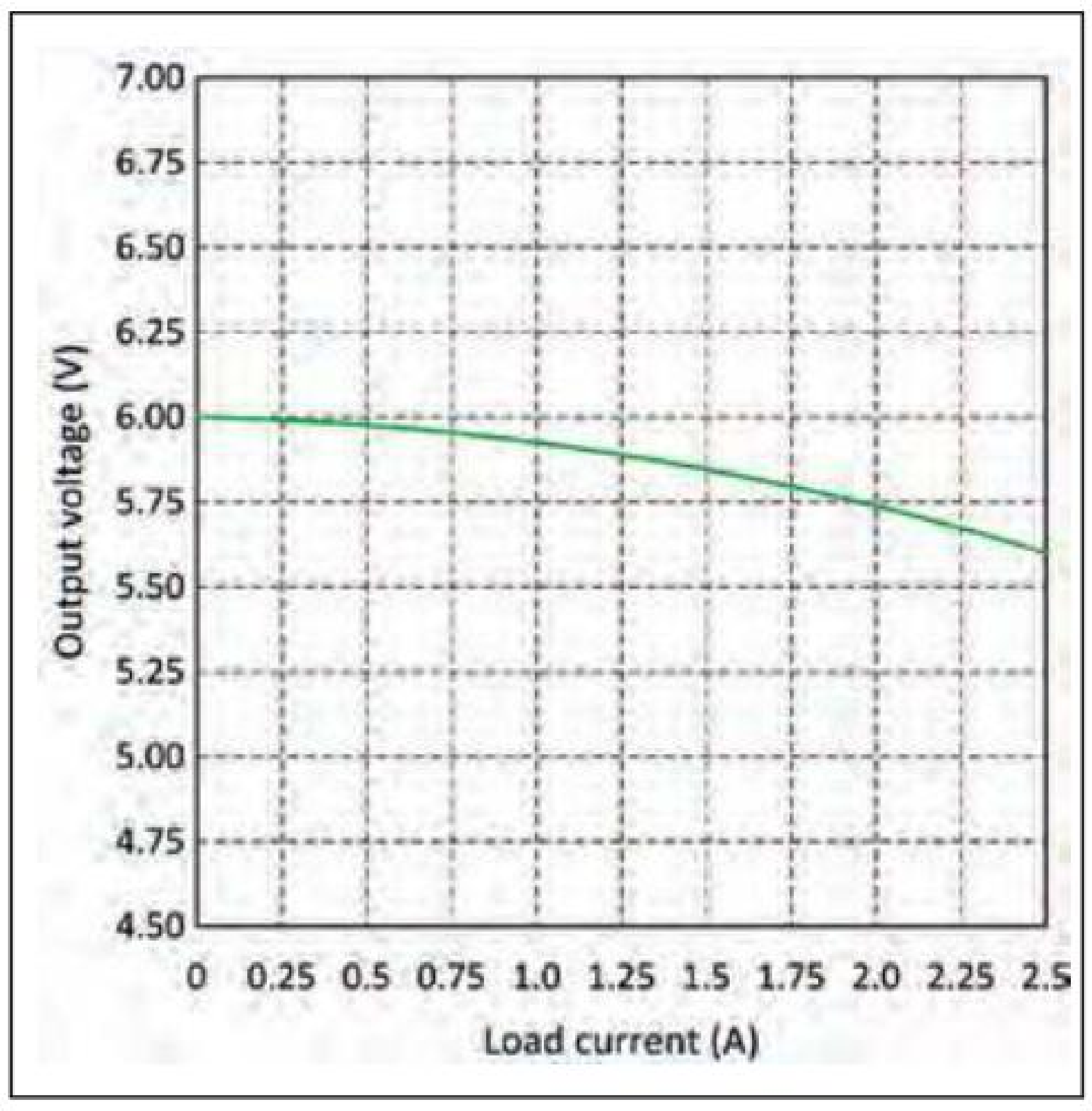


Fig.5.17. Load regulation characteristic for the SMPS regulator.

Get it Right! – Selecting equipment wire and cables

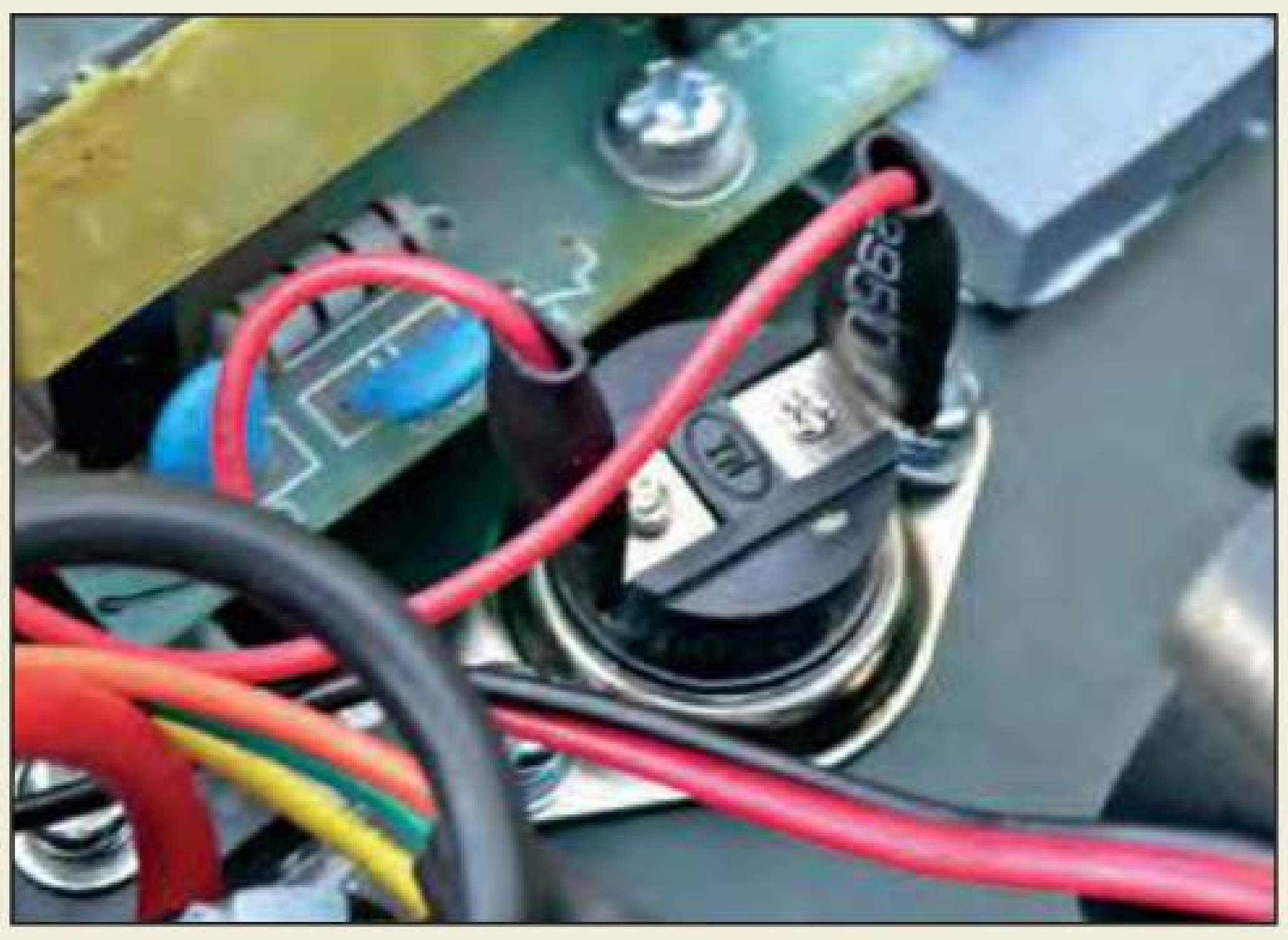


Fig.5.18. Power supply wiring should normally be based on insulated stranded equipment wire, which is both flexible and able to operate with the relatively high current present in most power supplies.

Last month, our *Get it Right* feature showed you how you to select the right fuse for your project. This month, we look at cabling and wiring. The choice of cables and wires can often be baffling. Most of us will be familiar with terms such as 'hook-up wire' or 'equipment wire', but what do these terms mean and how do you know that they are safe to use with the relatively high currents and voltages found in most power supplies?

Let's start with some basic properties of wires and cables, the most obvious of which relates to the diameter of the copper conductor used. We usually specify wire by means of a term referred to as 'standard wire gauge' (SWG) or 'American wire gauge' (AWG). Although these ratings are similar, they are not quite the same, as indicated in Table 5.1, which relates to the most common sizes of wire found in electronic equipment.

When a conductor is carrying current it may become warm due to the resistive I^2R power loss in the wire so we have included typical values of resistance (per metre), together with a recommended maximum continuous current rating (not the same as the 'current capacity' quoted by some manufacturers). The quoted recommended maximum current is that which can be used without significant power loss and temperature rise but, in many applications, it may be necessary to consider other factors such as ambient temperature, wiring layout and conductor length.

The term 'hook-up wire' usually applies to low-voltage / low-current applications and often comprises a single solid tinned copper core with a coloured PVC insulating outer jacket. Hook-up wire is fine for general use in electronic projects, but often inappropriate for use in power supplies where voltages and currents can be appreciable. For most applications, a stranded copper core will be necessary. This aids overall flexibility and because the current is shared between several conducting paths the overall diameter (compared with solid core wires) can be reduced for the same current flow.

Typical stranded 'equipment wire' consists of 16 individual tinned copper cores, each of 0.2mm diameter with an insulating wall of 0.3mm thickness and an outer diameter of 1.65mm. Such wires (20 AWG) are suitable for short runs (ie, less than 1m) carrying currents up to 3A at voltages of up to 1kV. Note that all *external* interconnecting cables should be double insulated (not only should the individual conductors be insulated but there should also be an outer jacket providing further insulation – think typical mains appliance cable).

Finally, it is well worth adopting a consistent colour-code system so that wires can be quickly and easily identified. The scheme adopted by the author is based on the resistor colour code and is shown in Table 5.2.

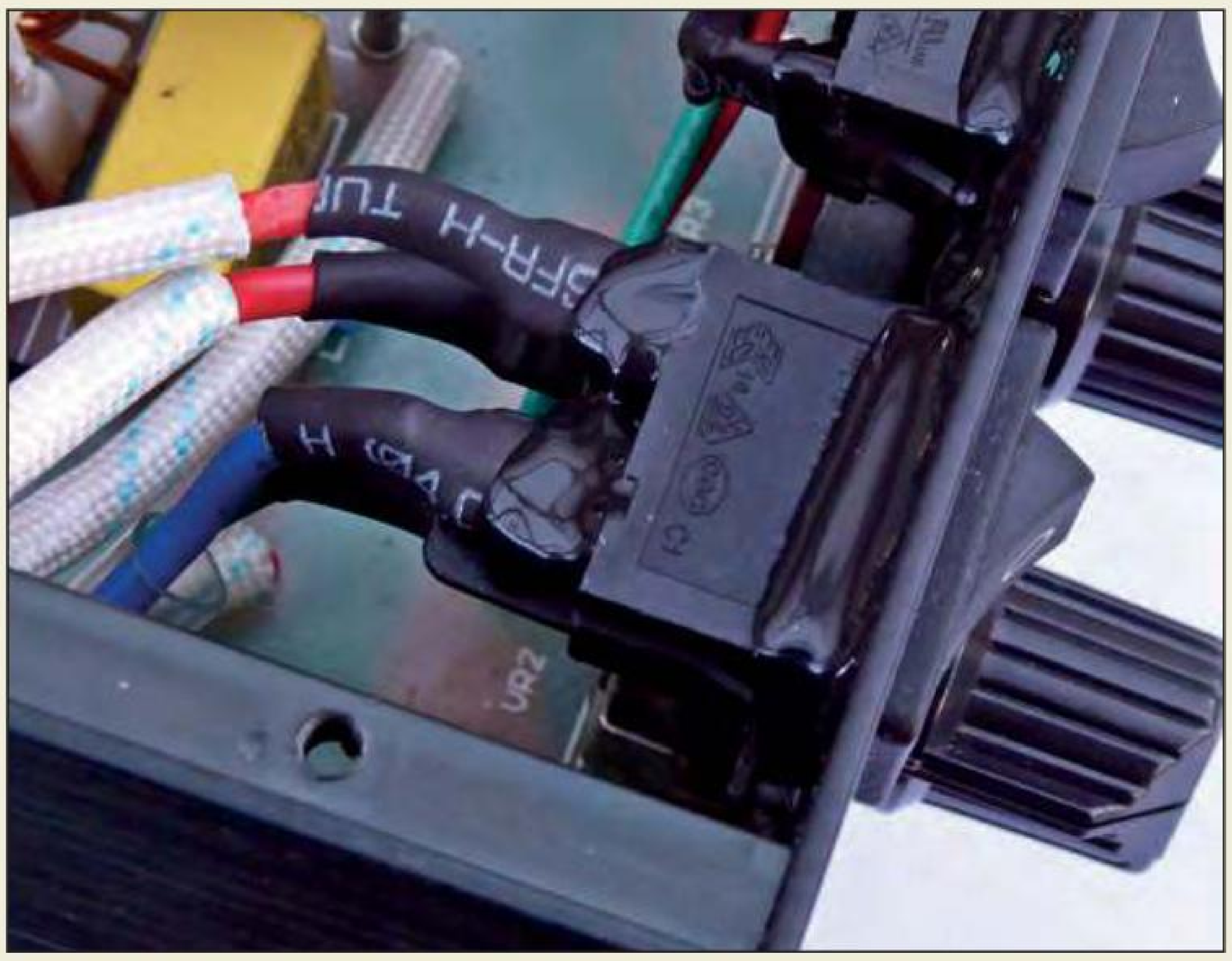


Fig.5.19. Additional insulation should be applied to equipment wire carrying AC mains voltages.

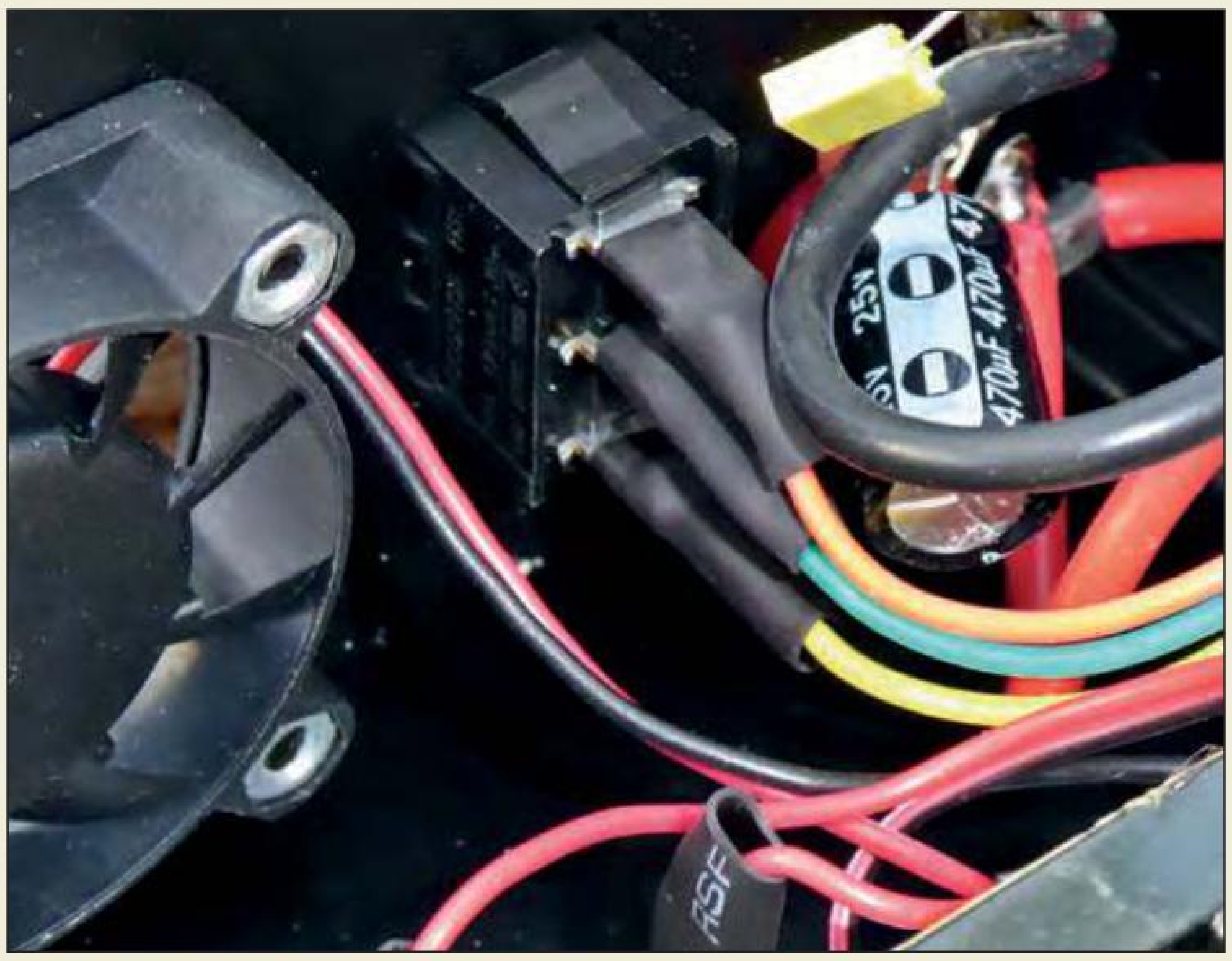


Fig.5.20. Colour-coded equipment wires can aid equipment assembly and fault finding.

SWG	Dia. (mm)	AWG	Dia. (mm)	Approx. resistance (per metre)	Recommended max. continuous current (A)
14	2.03	12	2.05	0.005	10
16	1.63	14	1.63	0.010	6
18	1.22	16	1.29	0.017	4
20	0.91	19	0.91	0.034	2
22	0.71	21	0.72	0.054	1.2
24	0.56	23	0.57	0.086	0.7
26	0.46	25	0.46	0.137	0.5
28	0.38	27	0.36	0.276	0.2

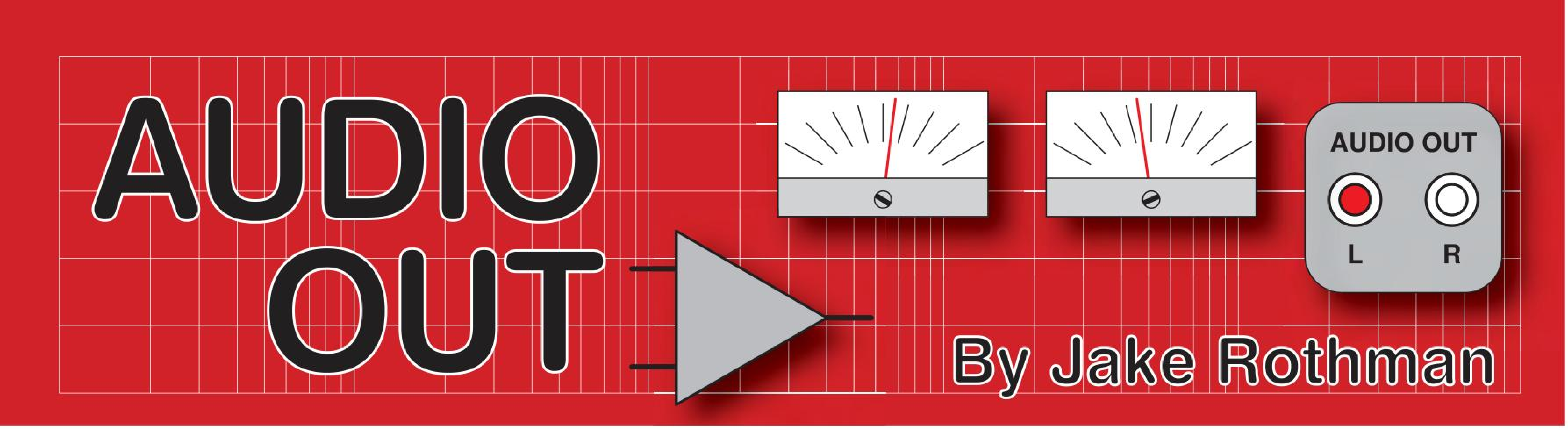
Table 5.1 Comparable SWG and AWG wire ratings.

Colour	Application
Black	0V (common negative supply)
Brown	Signal ground
Red	Positive supply voltage
Orange	Regulated supply (low-voltage)
Yellow	AC (low-voltage)
Green	Protective earth
Blue	Negative supply
Mauve	Standby supply (hot battery)
Grey	Control (power good)
White	High-voltage supply

Table 5.2 Colour coding for equipment wire.

AUDIO OUT

By Jake Rothman



Backing Baxandall – Part 1

Article by Jake Rothman
PCB and circuit by Mike Grindle

After volume and balance, tone controls are the most common audio process. Tone controls are essentially RC filters that alter the audio signal – cutting or boosting frequency bands according to the listener's taste. They are typically used to compensate for deficiencies in the audio chain, from source material to room acoustics. Much the most common tone controls are treble and bass, which appear in Hi-Fi amplifiers, electric guitar amplifiers and even effects pedals, as we will discuss in this article.

Acclaim without reward

How would you feel if you designed a circuit that was used in tens of millions of devices and you just got a $25 watch for it? That's what happened to Peter Baxandall, who invented the bass and treble tone control circuit used in nearly all audio amplifiers for the last 60 years. He never seemed to mind, being more interested in circuitry than money. If he was around today, in the culture of intellectual property, then it might have been a very different story. Having won the watch in a competition at the 1950 British Recording Association, aged 29, he refined his tone control and published it in the October 1952 issue of *Wireless World* – and everybody used it.

Passive vs active

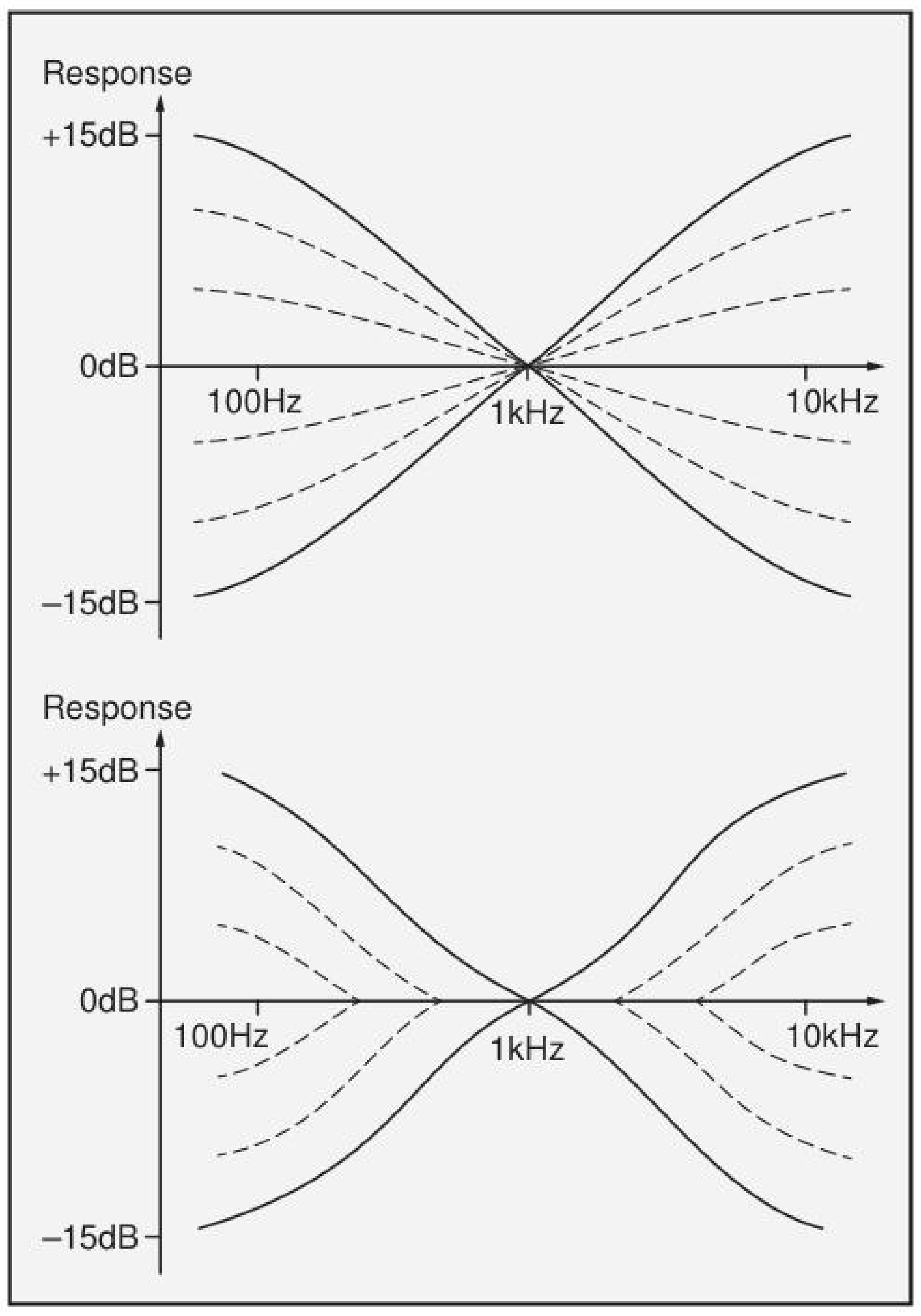


Fig.2. Difference between passive EQ curves and Baxandall's active equaliser: (top) Passive bass/treble lift and cut by varying response-curve slope; (bottom) Active bass/treble lift and cut by varying the pivot frequencies.

The first audio bass and treble controls were passive and consequently had high losses. In passive equalisation (EQ) circuits everything is attenuated except the frequency that needs to be boosted. This approach requires a lot of post-EQ gain, typically 18dB, resulting in high noise levels when set flat. To avoid this, the gain could be placed before the tone control circuit, but then that amplifier stage would be prone to clipping, reducing headroom. This headroom/noise conundrum has always afflicted audio design, but Baxandall fixed it by using an active approach; applying just the right amount of gain where it was needed. That's not all he fixed. Passive EQ circuits used logarithmic (log) pots, which introduce problems of availability and stereo matching, but Baxandall's design used standard, easy-to-source linear pots. For reference, a passive tone control is shown in Fig.1. R3 and R4 are loading resistors to ensure the response is flat in mid-position with the log Alpha pots specified. (Note that not all log pots are the same; for example, Alps and Alpha log pots have a different ratio (curve) from other manufacturers.)

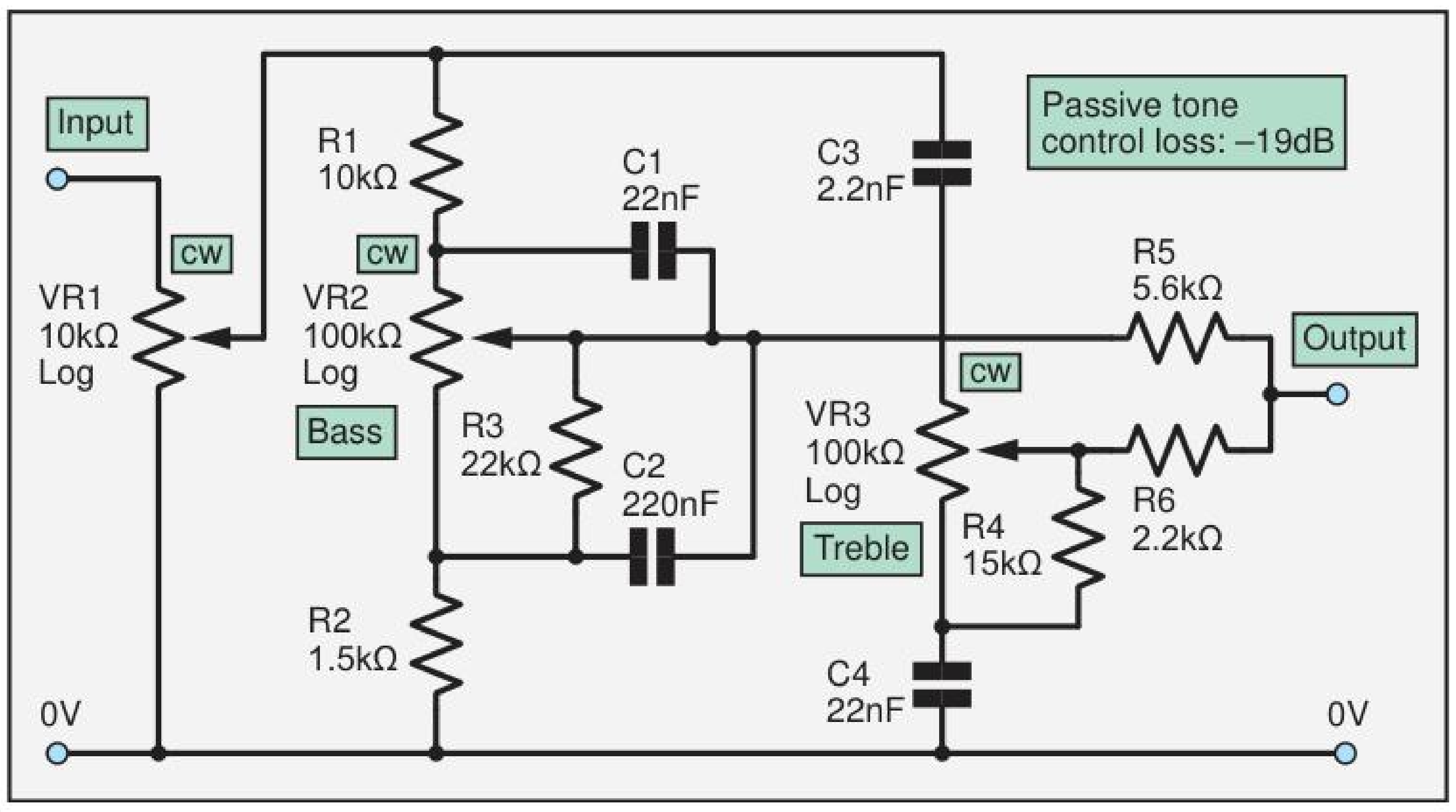


Fig.1. The original passive bass-treble equaliser, based on the EJ James design (*Wireless World*, February 1949) and used in many amplifiers until Baxandall improved it.

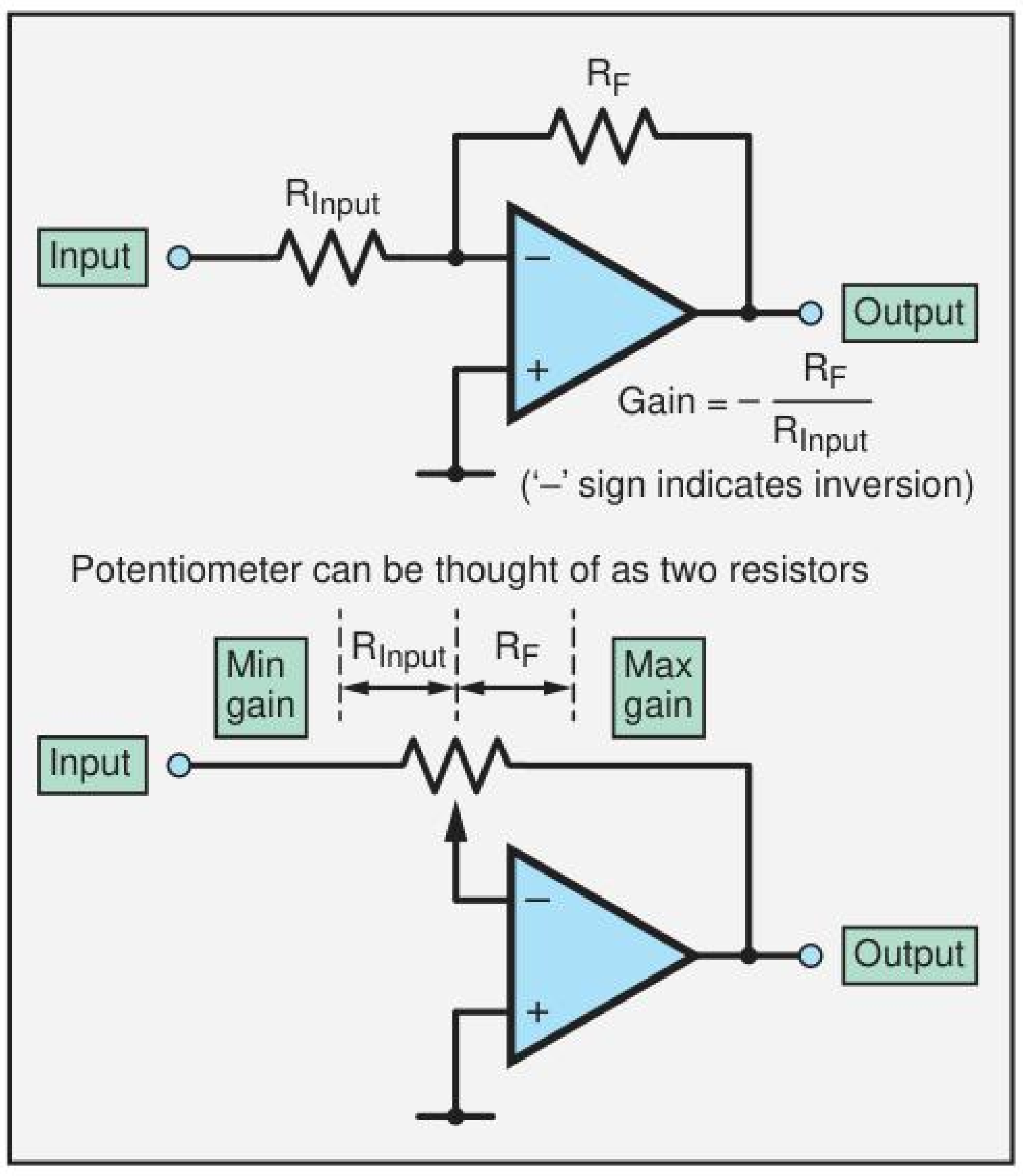


Fig.3. Inverting op amp with variable gain. Note that the pot can be thought of as two resistors: input resistance R_{in} and feedback resistance R_f.

Different curves

Classic bass and treble controls have a 'pivot point' in the centre of the audio band, at around 1kHz. The pivot point is the frequency unaffected by a tone control. Referring to Fig.2, cutting or boosting the treble cuts or boosts frequencies to the right of the pivot point only, and vice versa for the bass. There are differences in the way passive and active bass/treble controls behave, especially with respect to their pivot points. Subjectively, the passive curve sounds better because its pivot point does not move. With the active version of the treble control, the pivot point's frequency drops, moving towards the centre as the boost is advanced. This can have the effect of also boosting the mid-range as the

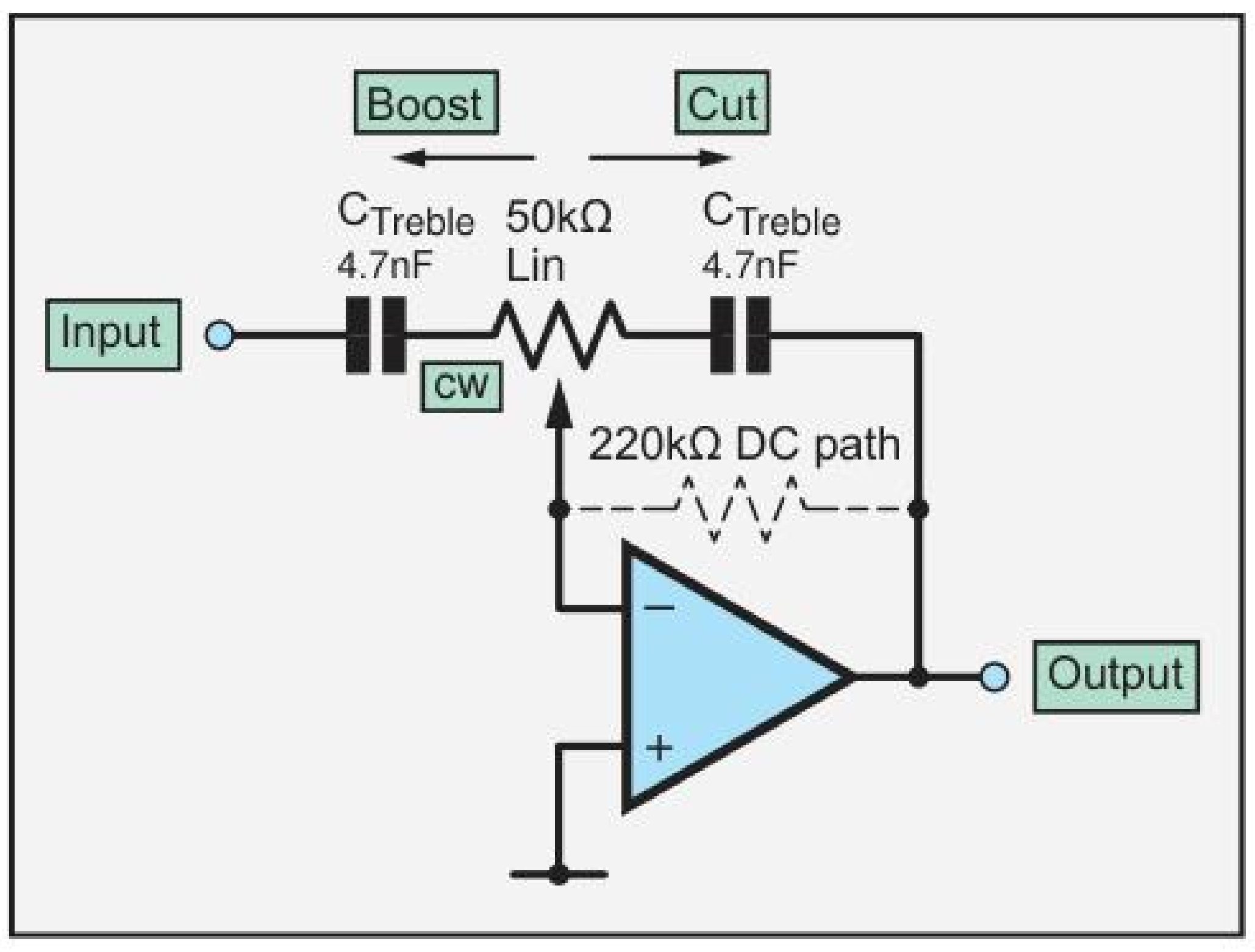


Fig.4. Converting the circuit in Fig.3 to variable treble gain by inserting capacitors.

treble is boosted, making it sound 'harder'. For the bass control, the pivot point frequency rises with bass boost, again boosting the mid-range signals. This effect sounds more noticeable, and hence is good for sales and cheaper speakers, if not audio accuracy. The difference between the two curves is shown in Fig.2. Japanese amplifier manufacturers combine the best of both with a special topology shown later which has a more subtle effect and works well with Hi-Fi amps driving high-quality speakers.

The Baxandall boost/cut curves are equal and opposite, which is seen as a virtue because if you apply too much correction to a recording it can be reversed. I also used to use it as a pre-emphasis/de-emphasis system to reduce noise in the days of analogue tape.

Bring on the valves

Baxandall's original circuit used valves, but is does not matter what type of active element is used – valve, bipolar transistor, FET or op amp – the principle is the same. The Baxandall design is based on the standard inverting amplifier configuration, and it's probably easiest to understand the op amp version in Fig.3, shown giving variable gain.

Baxandall – op amp version

In most Baxandall designs just one active element is used, and that will be the approach in the circuit built next month. However, the Baxandall control can be split into separate bass / treble sections to simplify analysis – typically one op amp each, whch reduces interaction between the controls. To make analysis simple, we will now look at the 'dual-active-element' approach, examining one control at a time.

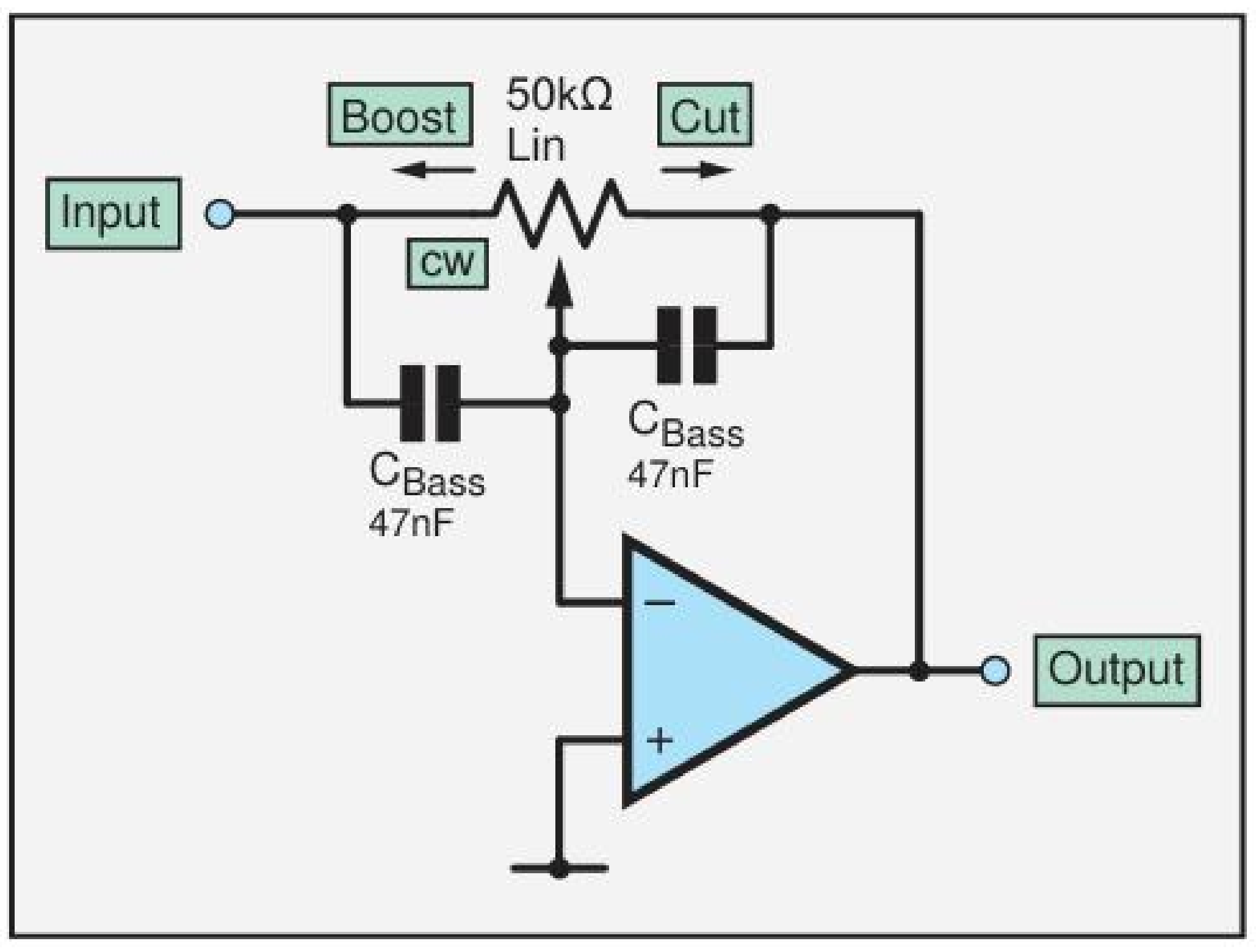


Fig.5. Making the inverting op amp circuit with variable bass gain.

Before we go any further, here is a very useful general tip. When analysing pot-based circuits, always look at the three main pot positions: fully counter clockwise, mid-point and fully clockwise.

Treble section analysis

First, we'll look at the treble section, as shown in Fig.4. When the pot is turned fully clockwise (wiper to the left – 'CW' on the diagram) boost occurs, because the total input resistance is low relative to the feedback resistance. Remember, with an inverting op amp stage, the gain is equal to the feedback resistor divided by the input resistor (see Fig.3). Because a capacitor is in series, boost only occurs at high frequencies. When the pot is fully counter-clockwise (CCW) the capacitor is effectively across the feedback resistor, making a simple first-order low-pass filter. This tells you that the maximum slope of the Baxandall is 6dB/oct (per octave). In practice, it rarely gets there, operating typically at 4dB/oct with a phase shift of less than 90°. The noise is only 6db more than the unity-gain op amp when set flat. This means it has a gentle effect on the sound, which meets with approval from most of the Hi-Fi fraternity. (There are purist audiophiles who disapprove of all tone controls. I should tell them just how many filters their music has been through during its production!)

Bass section analysis

Moving on to the bass control in Fig.5, the capacitors are in parallel with the pot rather than in series with it, so the effect is opposite to the treble control discussed above. The values are also much higher. When fully clockwise, (boosted) there is an RC network across the feedback capacitor, as shown in the equivalent circuit in Fig.6. It is effectively a 50kΩ feedback resistor with a 33nF capacitor across it. The other capacitor is shorted out. In 'cut mode', the capacitor is in series with the input, causing high-pass filtering or bass cut – the equivalent circuit is shown in Fig.6. Of course changing the values of the capacitors changes the pivot point and boost frequencies. For Hi-Fi, the bass capacitors are often bigger, and the treble capacitors smaller, to limit the effect to the audio extremes and minimise the effect on the mid-range.

Budget Baxandall

Since the bass capacitor is alternately shorted out at both extremes of the pot rotation, a single capacitor can be used, wired across both ends of the pot. This is called the Baxandall 'single-capacitor bass control' (here the pivot point is fixed). The treble capacitors can also be minimised by wiring one cap in series with the wiper. If this is done for both sections then we have the 'two-capacitor Baxandall tone control', as shown in Fig.7. This has the disadvantage of giving a low input impedance across the whole audio band when the treble is boosted, instead of just at the high frequencies being boosted. This loading effect on the preceding stage means it is not the best design for low distortion. If we go back to the 1960s when capacitors were expensive it might have been worth it. Nowadays, capacitors are cheap, but switches are still expensive, so I would use it today where I wanted switchable pivot point frequencies, because it would halve the number of gangs.

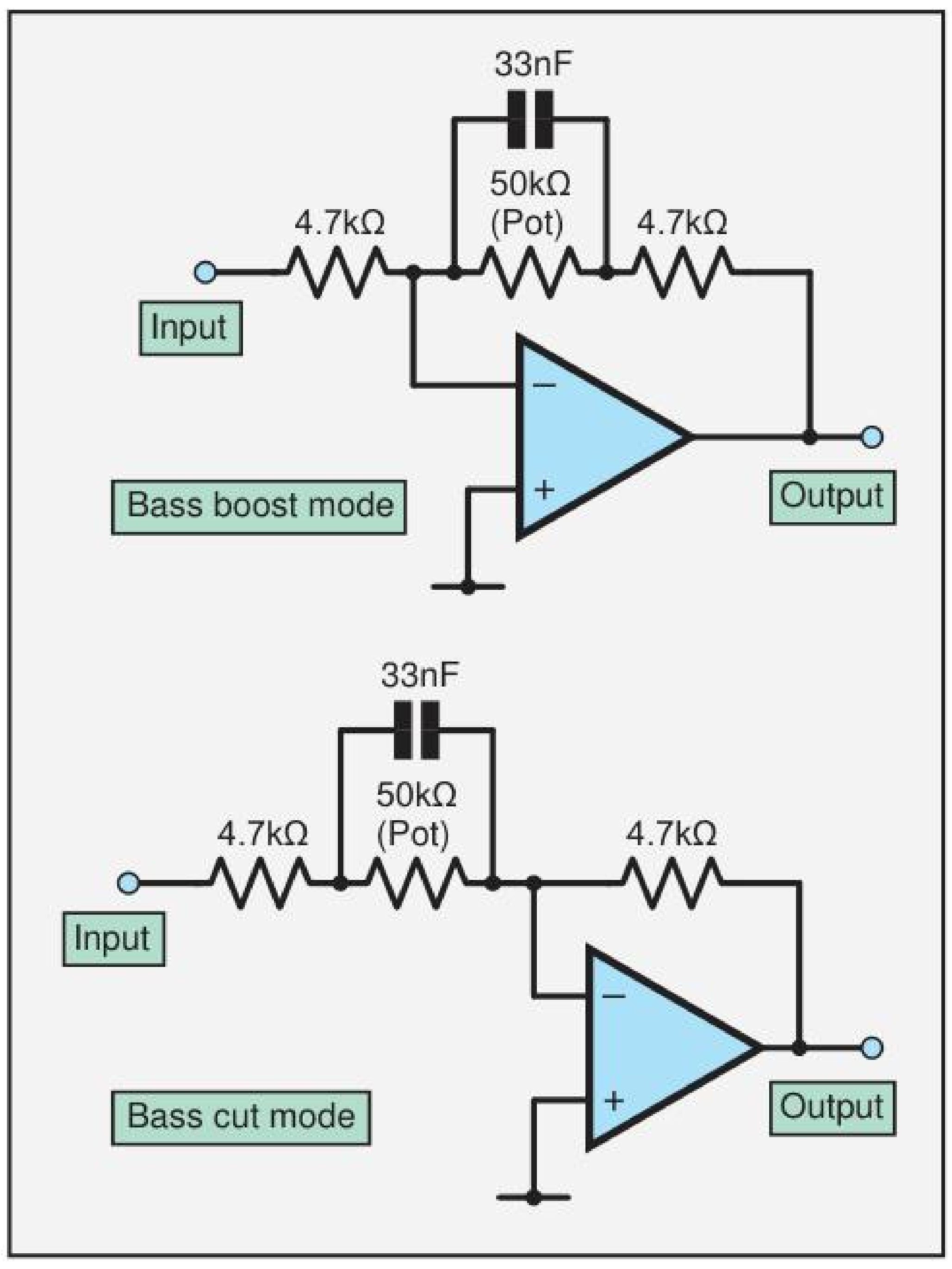


Fig.6. Equivalent circuits based on Fig.5, showing the effect of bass boost and cut pot positions.

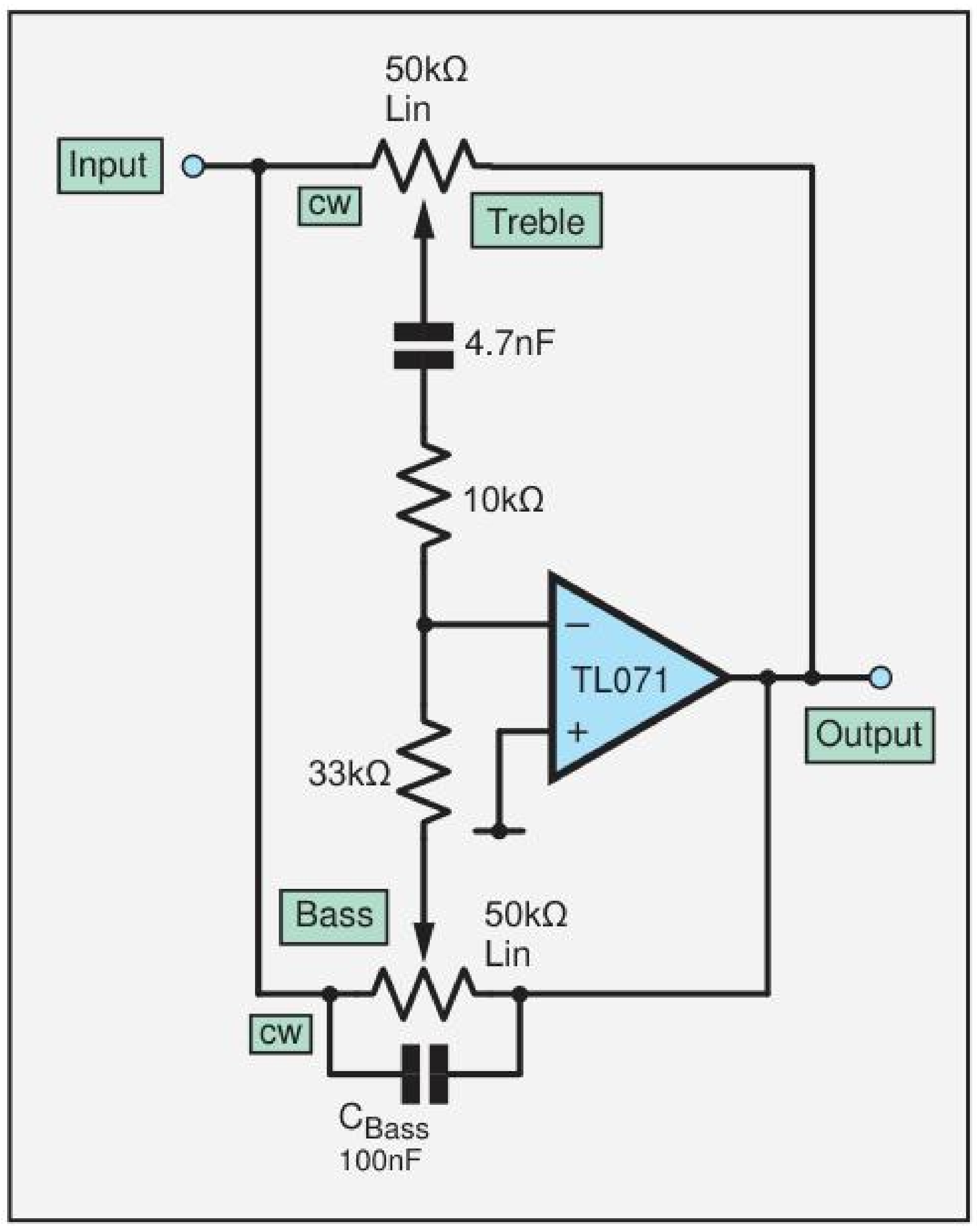


Fig.7. Budget two-capacitor Baxandall tone control.

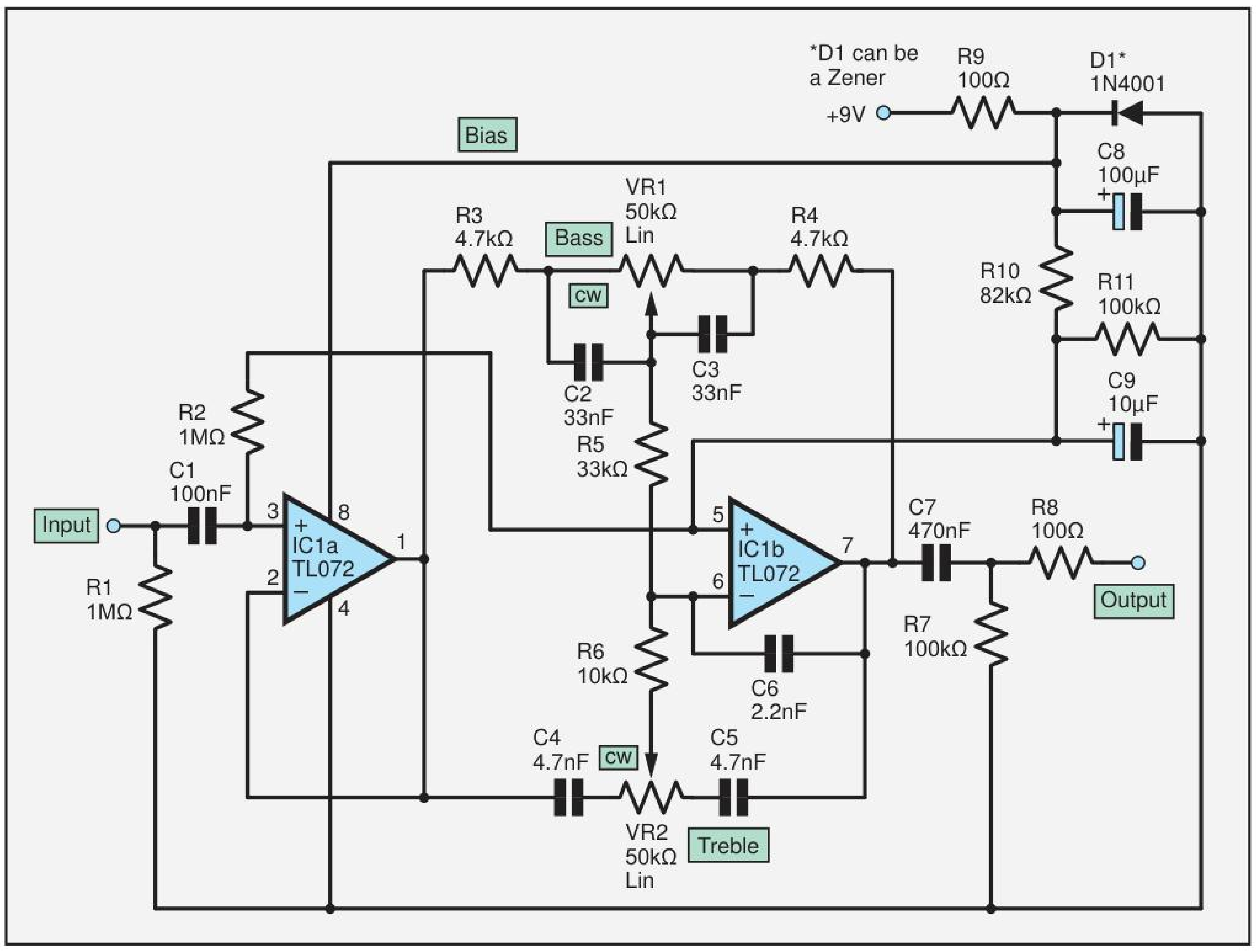

*D1 can be a Zener
+9V
R9 100Ω
D1* 1N4001
C8 100µF
Bias
R3 4.7kΩ
Bass
VR1 50kΩ Lin
cw
R4 4.7kΩ
R10 82kΩ
R11 100kΩ
C2 33nF
C3 33nF
C9 10µF
R2 1MΩ
R5 33kΩ
C1 100nF
Input
R1 1MΩ
IC1a TL072
IC1b TL072
C7 470nF
R8 100Ω
Output
R7 100kΩ
R6 10kΩ
C6 2.2nF
C4 4.7nF
C5 4.7nF
VR2 50kΩ Lin
Treble

Fig.8. Proper four-capacitor Baxandall tone control designed by Mike Grindle, the circuit for the PCB will be discussed next month in *Part 2* (Fig.19).

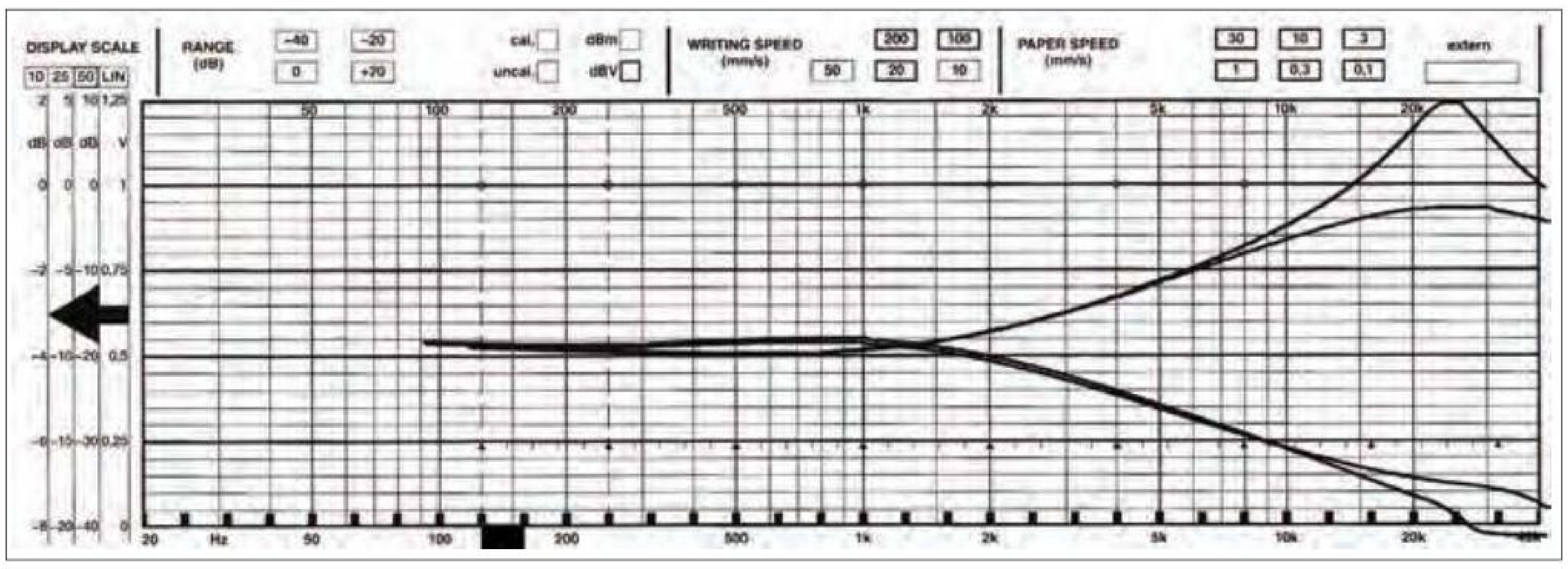


Fig.9. The effect of the Dinsdale 1961 mod to give a better treble boost. (This was used in the Delta 70 circuit in Fig.14.)

Four-capacitor Baxandall

For the design we're going to build we'll stick with Baxandall's original four-capacitor version. Combining the two sections to get the circuit in Fig.8. A PCB will be provided in *Part 2*. Note an additional resistor (R5), which is necessary to prevent interaction between the controls. There is a Y-Δ (wye/delta) trick developed by Toby and Dinsdale (*Wireless World*, December 1961) in their pioneering transistor Baxandall design that can be employed with the two-capacitor bass circuit to give extra treble boost. They added a 10nF capacitor to ground from the wiper. The effect is shown in Fig.9 and the circuit is in Fig.14. It works by preventing the HF shunting effect of the bass capacitors.

Stop resistors

All pots need stop resistors in series with both ends of the track to limit their range. It's not a good idea to allow the circuit to go to zero-ohms input impedance, producing very high, unstable values of gain. The treble maximum boost cut is limited by R6 to about ±15dB and similarly for the bass with R4 and R3.

Potentiometers action

It can be seen that when a pot is moved there is a simultaneous reduction in the input resistance as the feedback impedance is increased. Thus, there are two factors increasing the gain at the same time as the pot is rotated. This gives rise to a log action using linear pots, another Baxandall benefit. Often, centre-detent pots are used, which click in the middle to get a flat response. Sometimes the pots are not perfectly equal on both sides when set to mid position. Sugden, the Yorkshire amplifier builder, used to put trimmers across the pots so that the mid position could be tweaked to give a perfect square wave at 1kHz. The preset was four times the control pot value and simply wired in parallel.

Baxandall boffin

A deeper analysis of the Baxandall tone control can be found in Douglas Self's book, *Small Signal Audio Design*. For those who love number crunching, National Semiconductor's *Audio and Radio Handbook* (1980) is recommended.

The original valve version

The original Baxandall 1952 circuit used a pentode valve that is now hard to source. However, a later version uses the still-available ECC81 – see his *Inexpensive Pre-Amplifier* design (*Wireless*

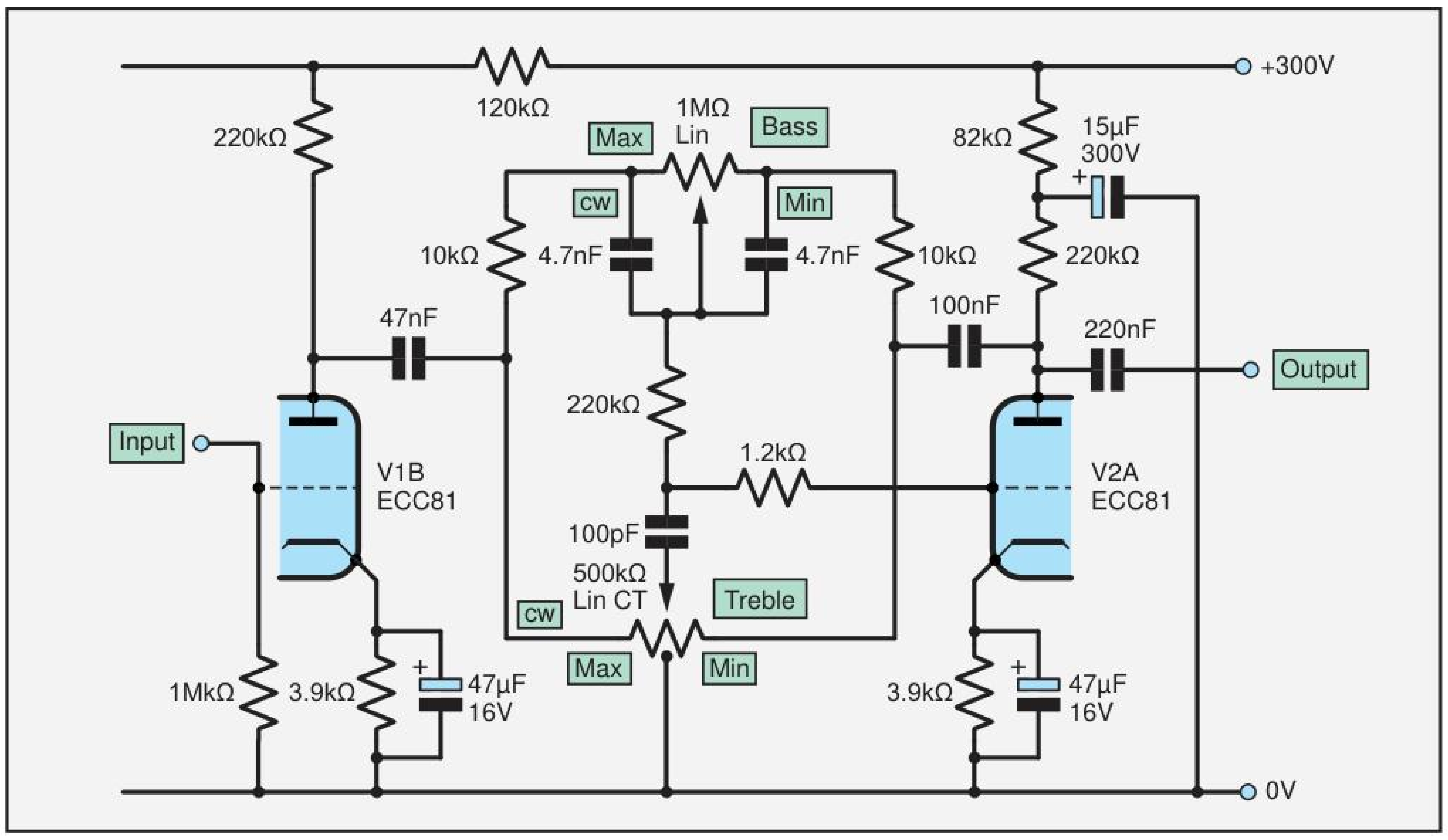

+300V
120kΩ
220kΩ
1MΩ Lin
Max
Bass
82kΩ
15µF 300V
cw
Min
10kΩ
4.7nF
4.7nF
10kΩ
220kΩ
47nF
100nF
220nF
Output
220kΩ
Input
V1B ECC81
1.2kΩ
V2A ECC81
100pF
500kΩ Lin CT
cw
Treble
Max
Min
1MkΩ
3.9kΩ
47µF 16V
3.9kΩ
47µF 16V
0V

Fig.10. A valve Baxandall circuit, notice the centre-tapped pot, which produces the 'passive-style' pivot point. The impedances are also much higher than are typical today.

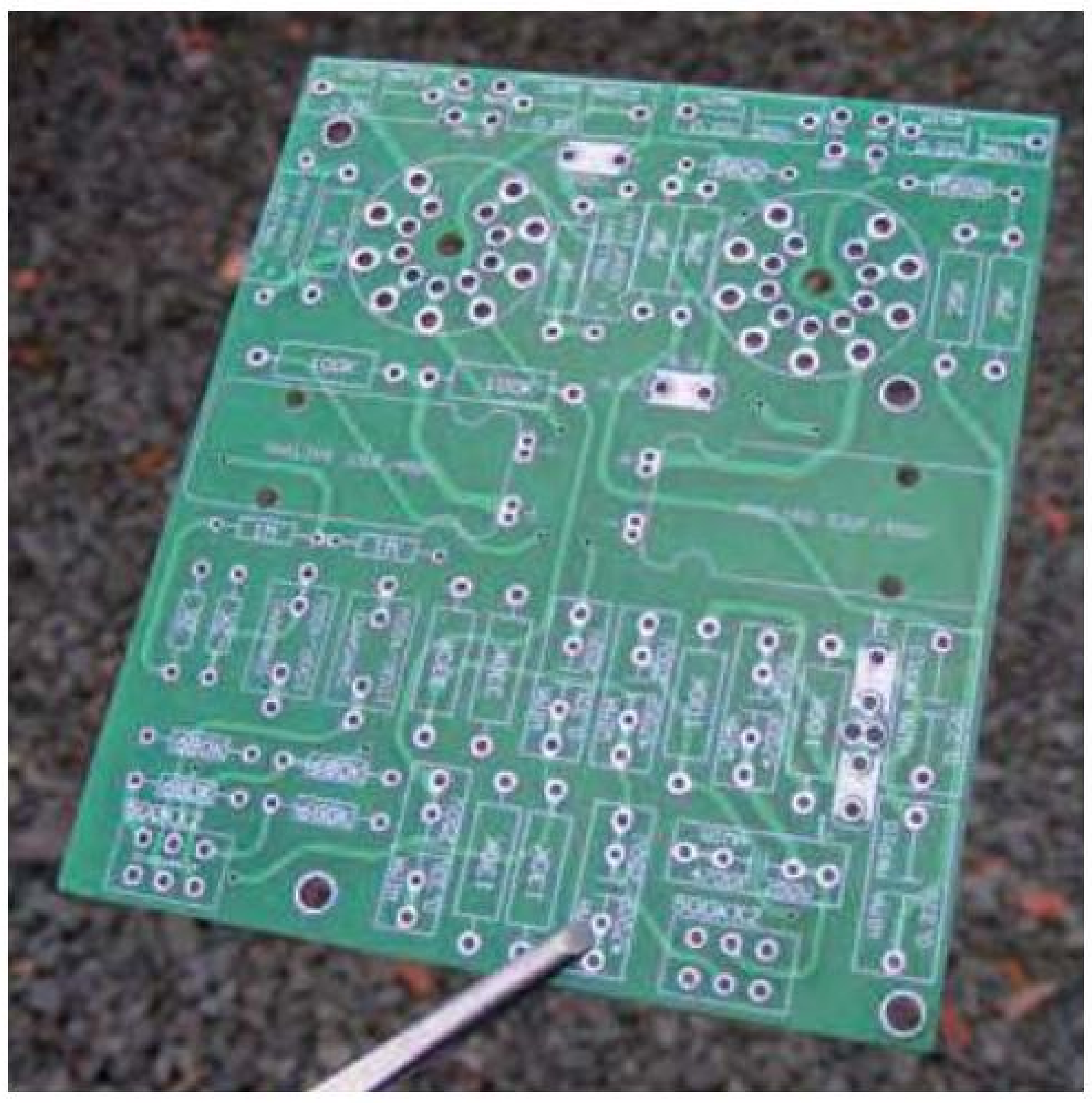


Fig.11. You can buy cheap valve-based Baxandall PCBs on eBay.

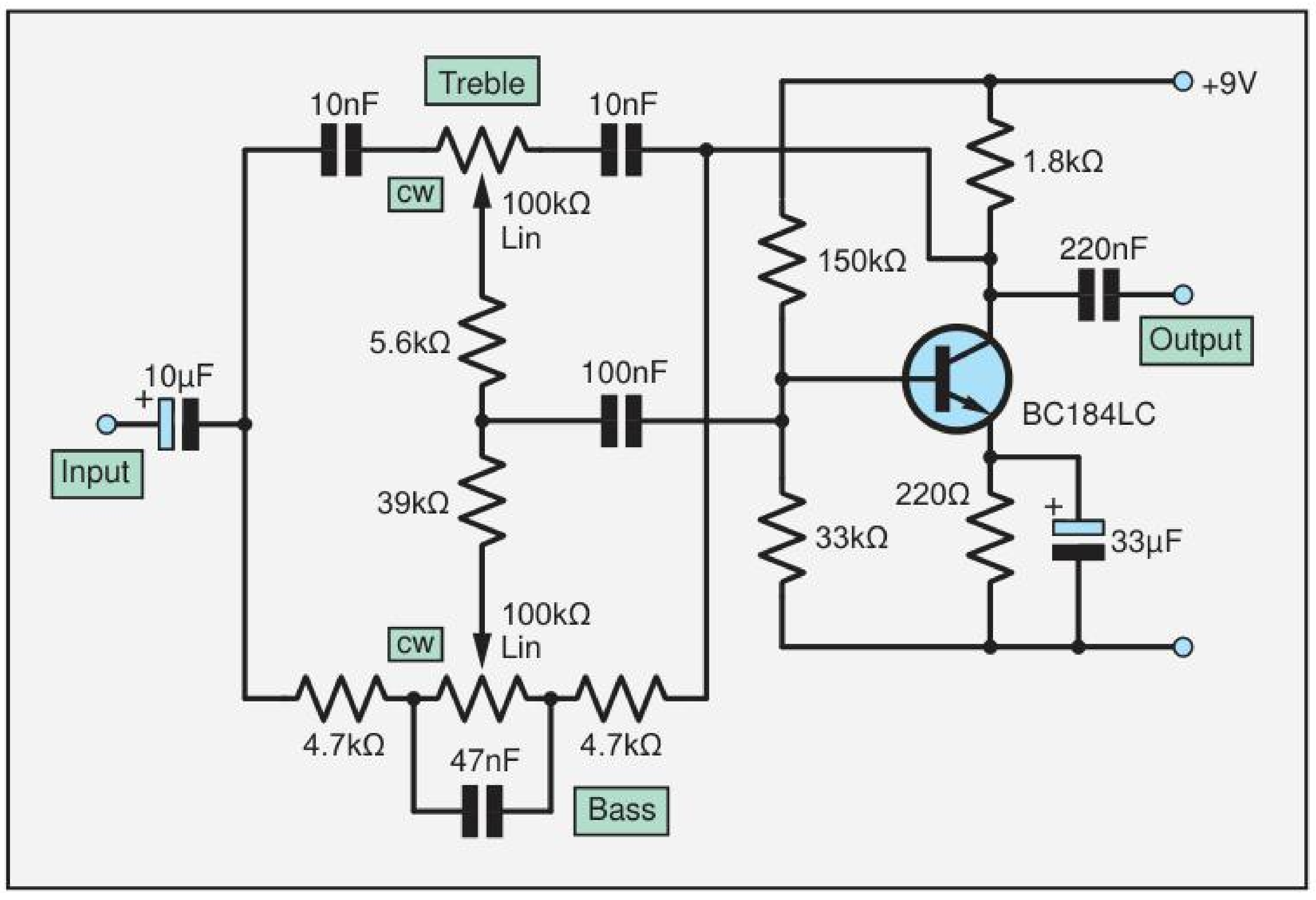
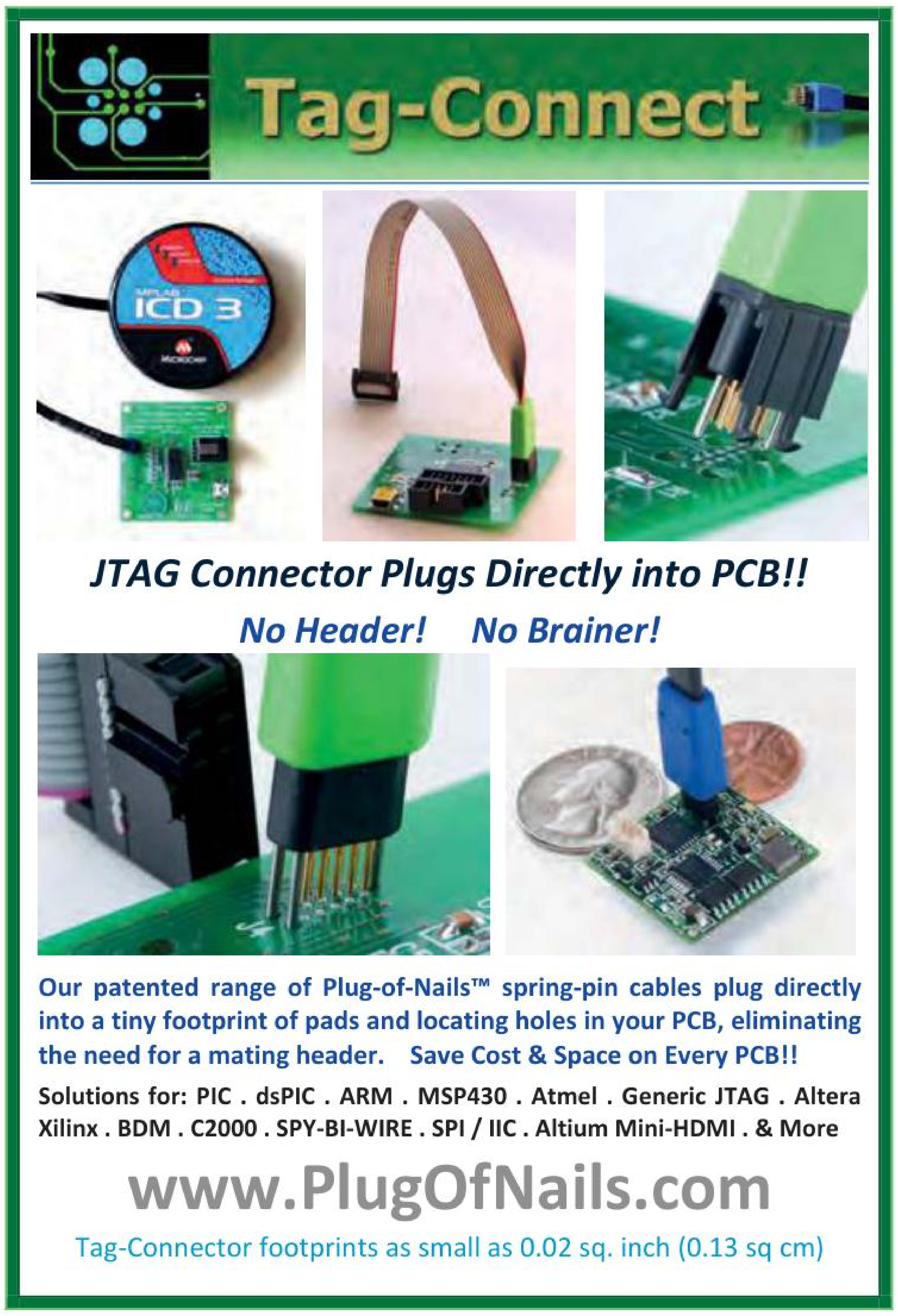

10nF
Treble
10nF
+9V
cw
100kΩ
Lin
1.8kΩ
150kΩ
220nF
Output
5.6kΩ
10µF
100nF
BC184LC
Input
39kΩ
220Ω
33kΩ
33µF
100kΩ
Lin
cw
4.7kΩ
47nF
4.7kΩ
Bass

Fig.12. Single-transistor version of Baxandall tone control used in the Colorsound Powerboost pedal.

World, May 1957). The circuit is shown in Fig.10. The specified centre-tapped pot is hard to obtain, but can be emulated to a degree by tying two 680kΩ resistors from each end of an ordinary linear 500kΩ pot to ground. The inverting feedback principle is the same, with the path going from the anode of the valve back to the grid, which is the virtual earth. This reduces the input impedance with the valve just as with an inverting op amp circuit. For this reason it is necessary to feed all Baxandall tone controls from a buffer amp or low-impedance source. (Vintage Hi-Fi fans will be pleased to know that PCBs for this circuit are available on eBay – see Fig.11.)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No Header! No Brainer!

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www.PlugOfNails.com

Tag-Connector footprints as small as 0.02 sq. inch (0.13 sq cm)

Colorsound Powerboost

The guitar pedal version of a Baxandall tone control is shown in Fig.12. It uses a single transistor, which is not recommended for Hi-Fi, since the distortion on full boost is in the order of 1%. No problem for a guitar pre-amp though. Fig.13 shows the curves – quite brutal for a Baxandall.

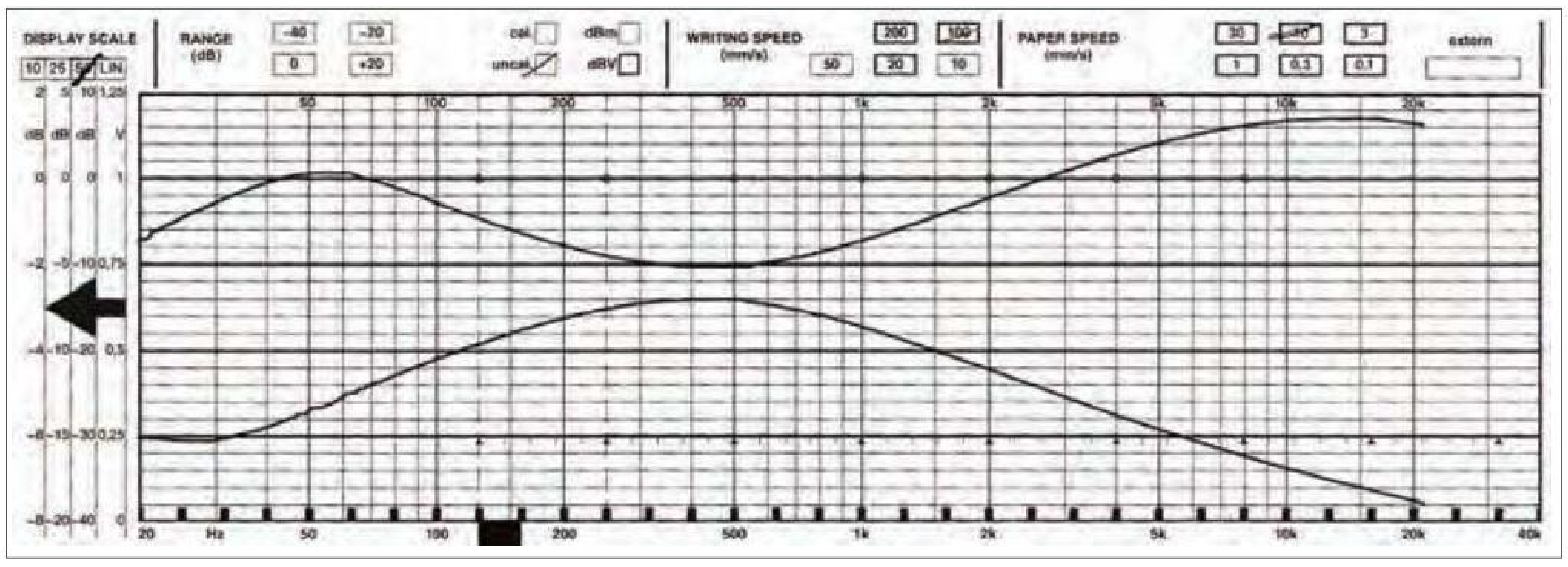


Fig.13. Frequency response curves for the circuit in Fig.12.

Low distortion version

The design in Fig.14, used in the well-regarded Leak Delta 70 Hi-Fi amplifier had a relatively high rail voltage of 48V, and with the addition of an emitter follower reduced distortion to about 0.1%. A further refinement by PM Quilter (see *Wireless World*, April 1971) was to add a bootstrap capacitor on the collector load of the first transistor. This greatly increased the open-loop gain from about 80 to 4000, giving a further reduction in distortion. Interestingly, the bass control has a higher resistance value than the treble control. I think this used to be common practice because it possibly allowed smaller value capacitors in the bass section. In the National Semiconductor book mentioned earlier, the treble control was bigger than the bass control. What is optimum? If anyone knows please let me know. I changed a few pot values and found this aspect of the circuit was particularly uncritical. So if you don't have the exact value, going one value step either way makes little difference.

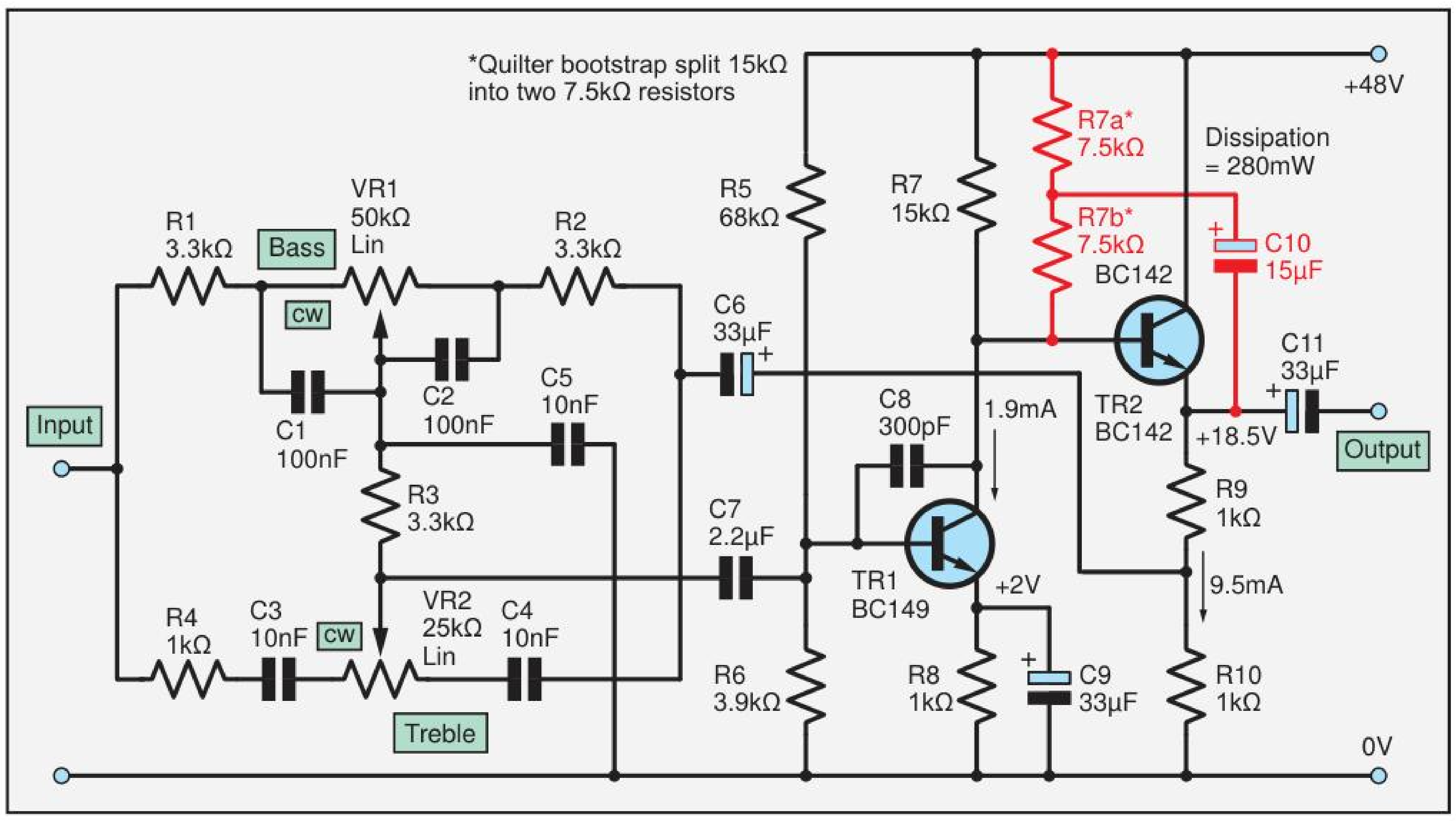
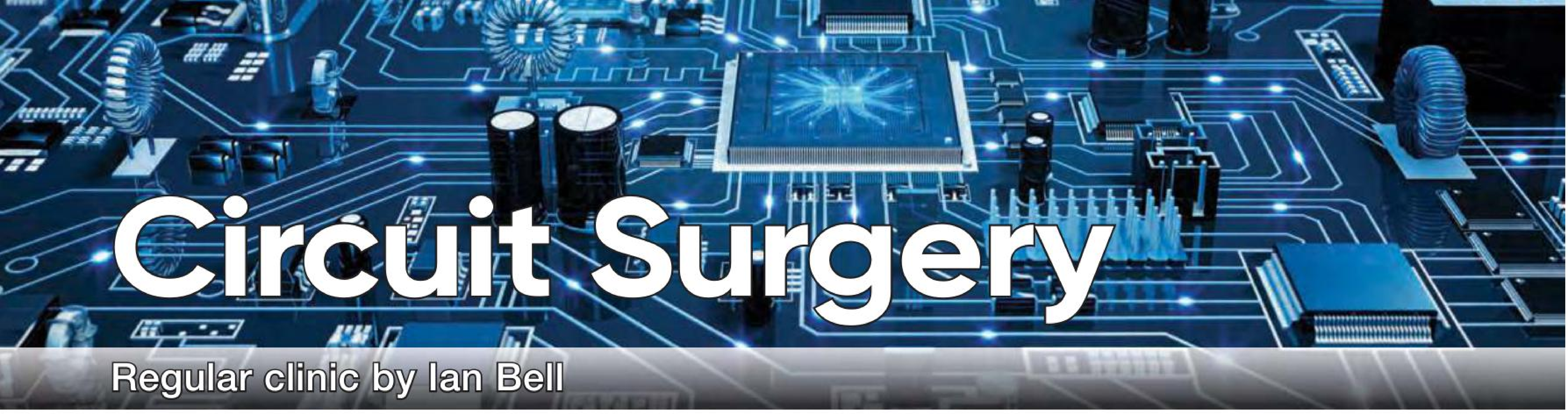

*Quilter bootstrap split 15kΩ into two 7.5kΩ resistors
+48V
R7a*
7.5kΩ
Dissipation = 280mW
R5
68kΩ
R7
15kΩ
R7b*
7.5kΩ
C10
15µF
BC142
R1
3.3kΩ
Bass
VR1
50kΩ
Lin
R2
3.3kΩ
cw
C6
33µF
C11
33µF
Input
C1
100nF
C2
100nF
C5
10nF
C8
300pF
1.9mA
TR2
BC142
+18.5V
Output
R9
1kΩ
R3
3.3kΩ
C7
2.2µF
TR1
BC149
9.5mA
+2V
R4
1kΩ
C3
10nF
cw
VR2
25kΩ
Lin
C4
10nF
R6
3.9kΩ
R8
1kΩ
C9
33µF
R10
1kΩ
Treble
0V

Fig.14. Leak Delta 70 tone control. This gives good Hi-Fi performance. The Quilter bootstrap improvement is shown in red (R7a/R7b replace R7). Note the extra capacitor (C5) to improve the treble characteristic, emulating the centre tap pot in Fig.10.

Next month

In *Part 2* we will build the four-capacitor Baxandall tone control in Fig.8.



Circuit Surgery

Regular clinic by Ian Bell

MOSFET power switches – Part 2

Last month, we started to look at the topic of MOSFET power switches in response to a post by Michael Ferguson on the EEWeb forum (**www.eeweb.com/forum**). In his post, Michael wrote:

'I'm working on the circuit in the attached image [Fig.1]. I've quickly realised there is not any good way to activate the V_{gs} of my power MOSFET with my gate driver. I've looked online at some other gate drivers, and all of them only output low voltages around 20-30V max.

Every single datasheet for gate drivers intended to be used with power MOSFETs describes their output in terms of current. Sink or source, up to 4A/6A, etc.

These are two of the gate drivers that I have [UCC20520 from Texas Instruments and ISL55110 from Renesas], one of them is also an isolated gate driver specifically used for power MOSFETs.

I understand that the MOSFET gates activate upon charging to a certain Q_g, but if the gate voltage needs to be 10V > than V_S, and V_S is 200V+, how is it possible to turn the gate on and let current flow from V_S to V_D?'

MOSFET basics

In last month's article we introduced some basics of MOSFETs in general, and power MOSFETs in particular. In the context of power electronics, MOSFETs are used as electronically controlled on/off switches in which conduction between the source and drain terminals is controlled by the gate-source voltage. There are two types of MOSFET: N-channel and P-channel. An N-channel device requires a positive gate-source voltage to switch on, and a P-channel device requires a negative voltage. Last month, we briefly described the basic principles of this switching operation with reference to structure and physics, and examined the layout of power MOSFETs, which allows them to handle high currents. We also looked at Michael's circuit (Fig.1) and discovered that the Zener regulator was not able to provide the 220V supply at anywhere near the 4.4A current implied by the 50Ω load. Assuming a better 220V supply, an N-channel MOSFET (as used in Fig.1) is able to switch the load, but requires a control voltage in excess of the 220V supply voltage.

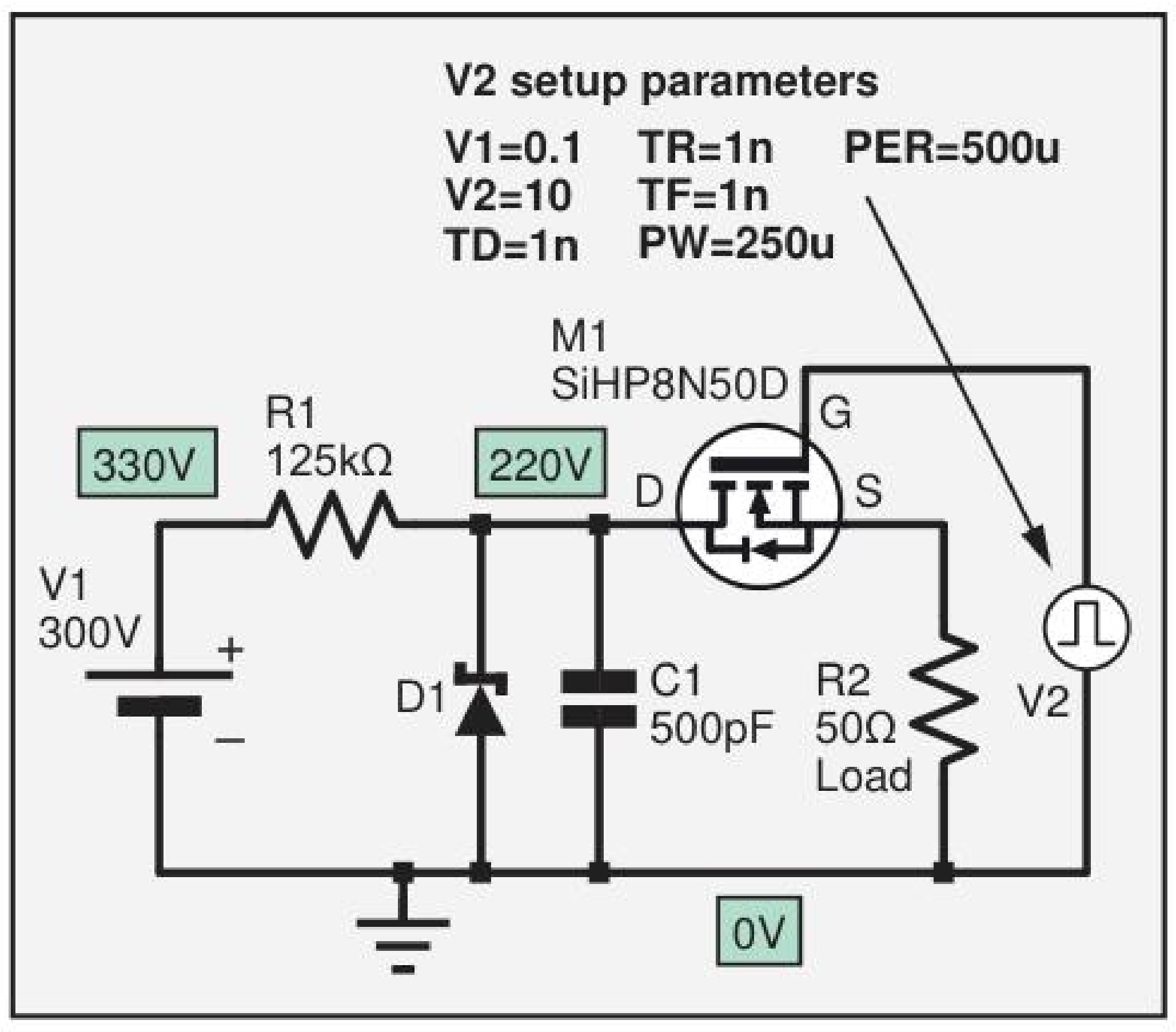


Fig.1. Michael's circuit, redrawn from his EEWeb post.

This month, we will look at some of the various circuit configurations for MOSFET switches and examine approaches to switching on MOSFETs in circuits like Fig.1. We will analyse an example of such a circuit based on the UCC20520 mentioned by Michael, and finally make some brief comments about switching inductive loads such as motors.

The circuit arrangement in Fig.1 is referred to as a 'high-side' switch because the MOSFET is connected between the supply and load (on the high-voltage side of the load), as opposed to being located between the load and ground (switch on the low-voltage side of the load). For an N-channel high-side switch, when the load is on, the MOSFET's source terminal is at the load voltage. However, in order to switch on the MOSFET, its gate-source voltage must be above the MOSFET's threshold voltage, which implies the gate must be at a higher voltage than the load supply. Power MOSFET threshold voltages are typically around 4V or 5V, but in order to turn on fully enough for use near their maximum current rating, many of these devices may need 10V or more. So for the circuit in Fig.1, a gate voltage of about 230V is required.

MOSFET drivers

The 10V relative to ground used in Fig.1 as the gate control will be insufficient to fully switch on the load. The 10V *change* in gate voltage is fine, but it needs to rise from 220V to 230V, not 0V to 10V. We investigated this behaviour of the circuit in detail last month through a couple of simulation examples. This leads to the core issue of Michael's question – how do you provide a gate voltage above the load voltage, particularly when the control circuit is likely to be operating on a much lower supply than the load voltage? The answer is that you need a suitable 'MOSFET driver' circuit. Although the high-side switching just discussed provides obvious challenges, even low-side switches, where the switching voltages required are more straightforward, are not necessarily trivial. Low-side switches also require appropriate driver circuits, particularly for high performance or demanding switching applications, and where control circuits are running on lower voltages (eg, 3.3V rather than the voltage required for low-side switching – eg, 10V).

The job of the driver circuit is to make sure the MOSFET is switched between fully on and fully off, by switching the gate-source voltage between 0V and some voltage well above the threshold. As discussed last month, use of voltages well above the threshold ensures saturated operation, in which the voltage drop across the device caused by the ON-resistance ($R_{DS,\,ON}$) and hence the power dissipation are minimised. In order for power MOSFETs to switch quickly and efficiently, sufficient current must be available to quickly charge or discharge the input capacitance of the device. During the transition between the on and off states the device may dissipate a lot of power, a problem referred to as switching losses. The drive circuit therefore must be able to supply enough transient current to charge the MOSFET input capacitance at the required rate. In some cases this current may be quite substantial, particularly for large, very-high-power devices, or where paralleled MOSFETs are being used.

Simulation files

The LTSpice files discussed in *Circuit Surgery* are available for download from the *PE* website.

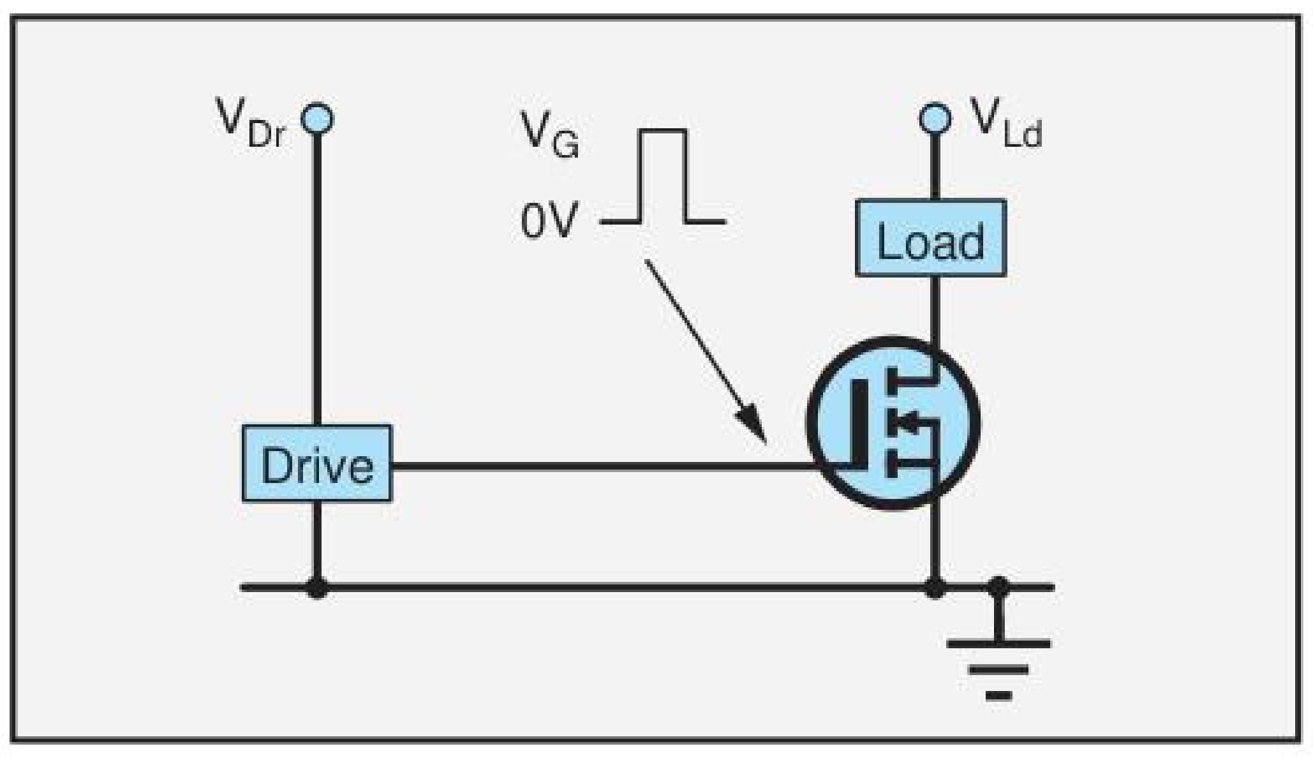


Fig.2. N-channel MOSFET low-side drive.

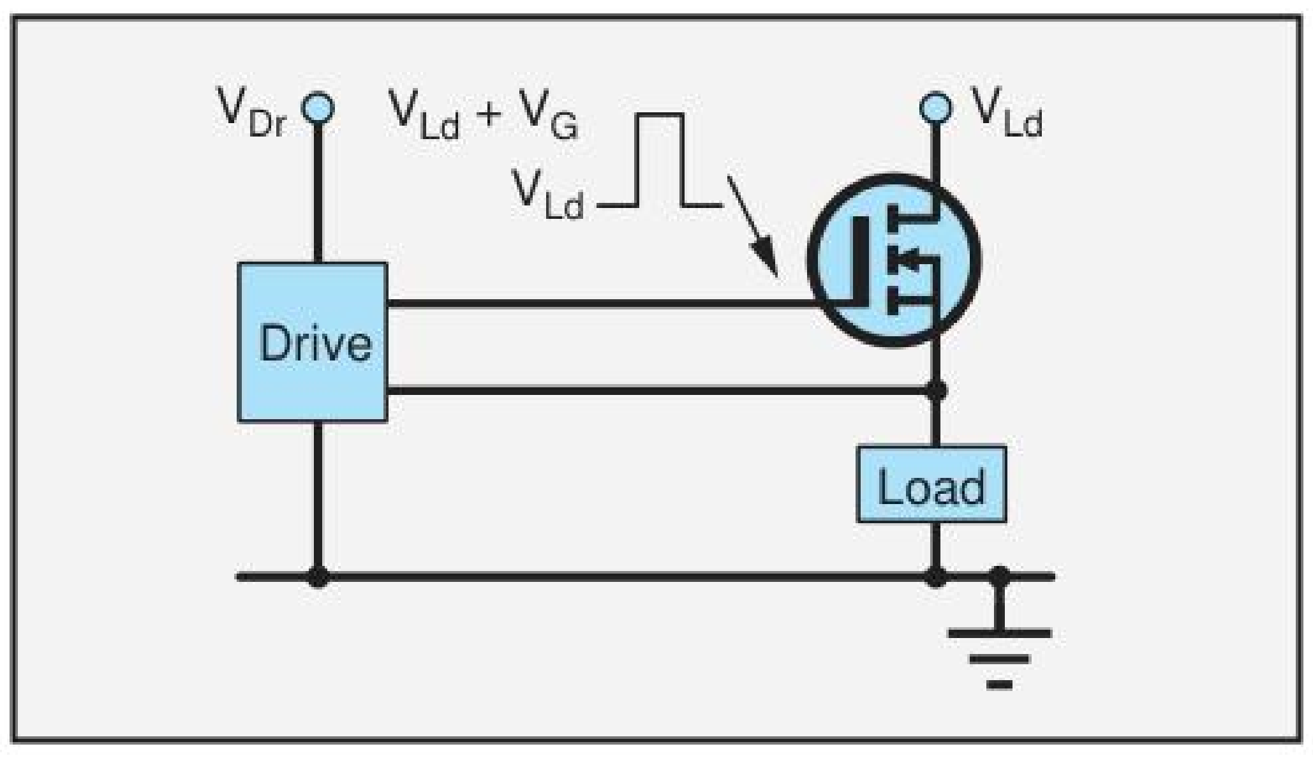


Fig.4. N-channel MOSFET high-side drive.

Many low-power circuit outputs, such as logic gates and microcontrollers simply cannot deliver enough current to drive the gate of power MOSFET correctly. A power MOSFET driver is therefore a power amplifier that accepts a low-power input from a microcontroller or other circuit and delivers the required high-current gate drive to the MOSFET. Gate drivers may be implemented as dedicated ICs, discrete transistors, or transformers. The circuits can be quite complex, particularly for high-side drivers and when switching multiple MOSFETs in arrangements such as bridges (see later), so the use of dedicated ICs can save a lot of effort.

At first, the complexity of drivers may seem unnecessary, but seemingly small imperfections in the control of devices switching very large currents or high voltages can have significant consequences, potentially causing MOSFET failure. As w being too slow it is also possible for power MOSFET circuits to switch too fast, or put more accurately, for voltages or currents within the circuit to change too fast. Very fast current and voltage changes can damage devices and also cause more interference radiation than slower switching. Careful design of the driver circuit may be required to get the switching behaviour correct, particularly in high-speed and very-high-power applications.

Switching configurations

As has already been indicated, there are a number of different switching configurations in which power MOSFETs are used, and these may require different types of driver. With a single transistor we can employ N-channel or P-channel devices, and we can use low-side or high-side switching. If we require the load to be grounded, or if we are using a bridge circuit, then we need a high-side switch. N-channel devices are often preferred because the inherently higher conductivity of n-type silicon leads to higher performance devices. High-side switching, however, is often easier to implement with P-channel devices.

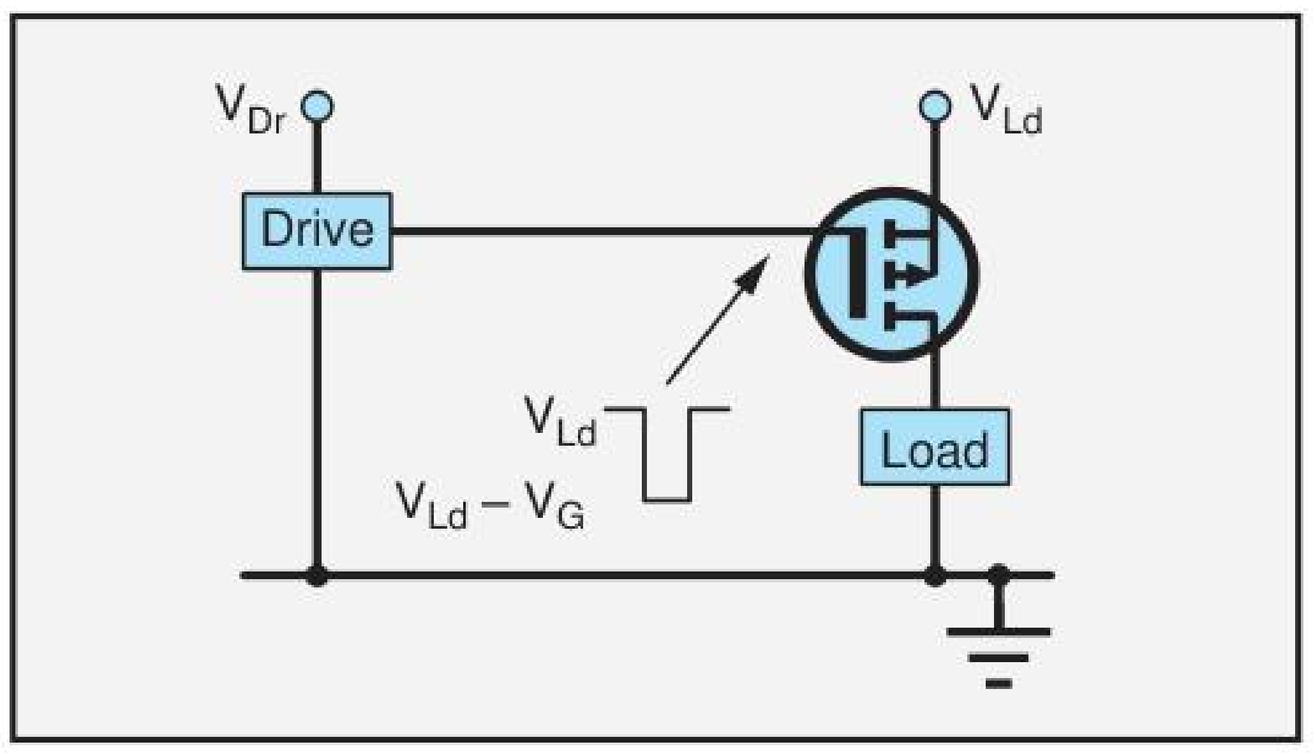


Fig.3. P-channel MOSFET high-side drive.

Fig.2 shows an N-channel low-side switching arrangement. The driver circuit has to switch the gate between 0V (off) and V_G (on). The power supply voltage for the driver (V_{Dr}) will often be greater than or equal to V_G, but may be much less than the load power supply voltage (V_{Ld}). V_G is not the threshold voltage (V_T) but a larger magnitude voltage, as discussed above, which is required to fully turn on the MOSFET. Fig.3 shows a P-channel device used as a high-side switch. The gate voltage is switched from V_{Ld} (off) to $V_{Ld} - V_G$ (on). Fig.4 shows another high-side switch, in this case using an N-channel MOSFET, and therefore requiring a gate voltage higher than the load supply voltage by V_G volts to switch the transistor on – this is the arrangement required in the circuit in Fig.1.

Bridges

Switching circuits using single transistors are shown in Fig.2 to Fig.4. Other switching circuits, specifically the half-bridge or full-bridge (H-bridge) configurations, use more transistors – with at least one on each side of the load. Drivers for these configurations require the capabilities of both high-side and low-side circuits. We show two examples here – Fig.5 is a half-bridge circuit using a complementary pair (both N and P transistors) and Fig.6 shows an H-bridge using just N-channel devices. The half-bridge is commonly used in switched-mode power supply designs because it allows more efficient circuits with lower electromagnetic interference (EMI) to be designed. The H-bridge circuit is different from the other circuits presented here, in that it enables the polarity of the voltage across the load to be reversed. It has a wide range of uses, including motor controllers and DC-to-AC power inverters. (The name 'H-bridge' comes from the shape of the schematic in which is load is the middle bar of the 'H'.)

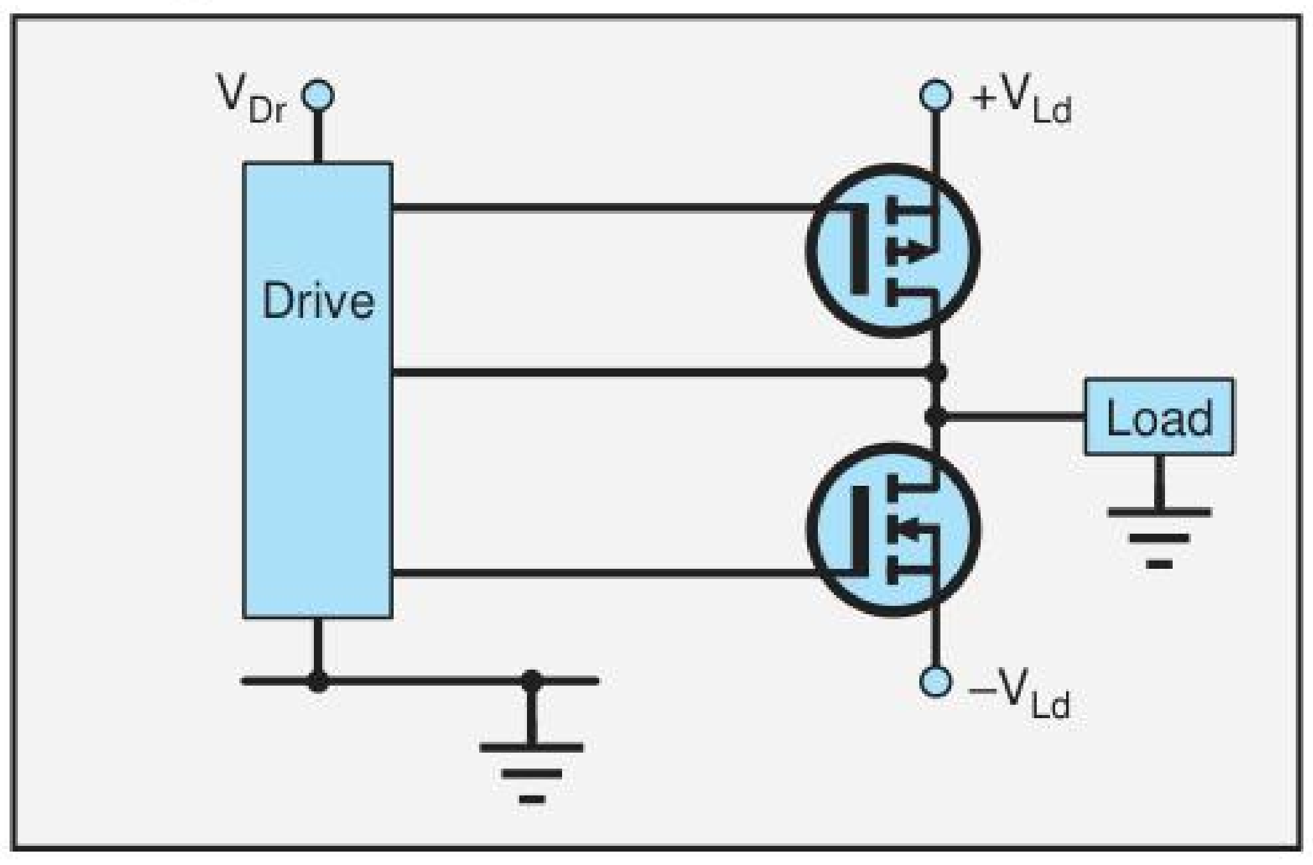


Fig.5. Complementary pair half-bridge driver.

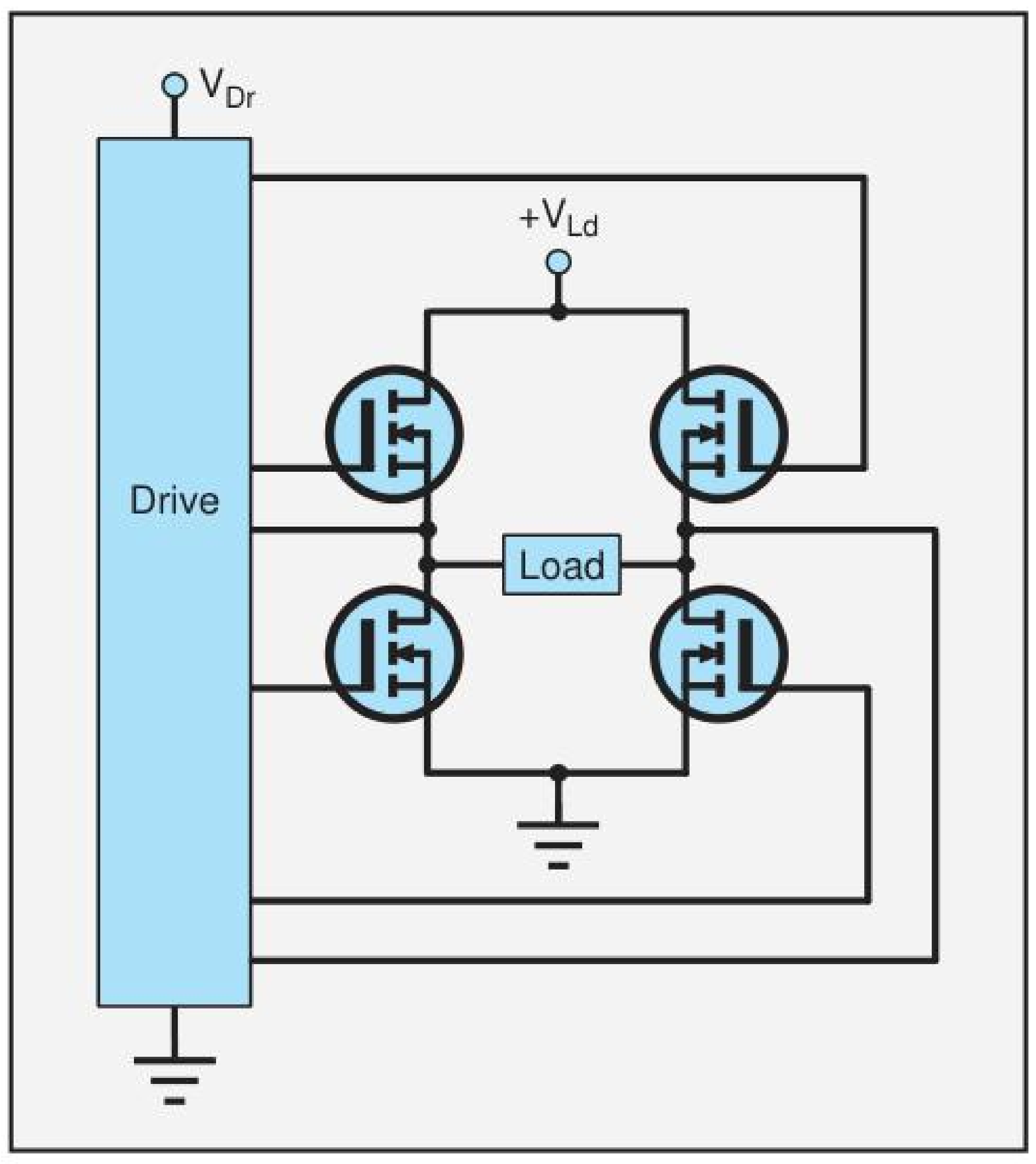


Fig.6. Full-bridge driver using n-channel devices.

An additional concern with half- and full-bridge drivers is the possibility of briefly switching on both transistors in a half-bridge at the same time, resulting in excessive crossover, or cross-conduction current flowing as one transistor on is switched on and the other off. Driver circuits must control the timing of the switching of the two transistors to prevent this from happening. Some drivers have adjustable deadtime – that is time during changeover when both transistors in the half-bridge are off.

High-side drivers

For high-side switches there are a number of techniques which can be used to obtain the voltage levels above the load supply voltage required to switch the transistor. Boostrap high-side drivers charge a capacitor using a low voltage supply and switch the capacitor to the gate-source of the MOSFET to turn it on. This approach cannot hold the transistor on indefinitely, as the bootstrap capacitor has to be recharged periodically (while the high-side MOSFET is off). Charge-pump high-side drivers use voltage-multiplier circuits to generate the high gate voltage. They can be inefficient and slow, but allow indefinite high-side on time. A pulse transformer can be used to couple the control signal to the high-side gate, this is potentially simple and low-cost, but can be quite difficult to get right in practice. A floating power supply can be used for the high-side drive circuit with switching controlled via an opto-isolator. This is an expensive option because a separate supply is required for each high-side MOSFET used.

The above is not an exhaustive list of techniques and there are a number of variations on each basic idea. Having mentioned isolation, it is worth pointing out that this will often be required for safety reasons, to separate the low-voltage control circuitry from a much-higher-voltage load.

Design of high quality power MOSFET driver circuits from scratch is not very easy, except perhaps for relatively undemanding situations. This is particularly true if high-side switching is required. Fortunately, there are many driver ICs available that do most of the work for you. Furthermore, the manufacturer's datasheets, or associated application notes, will often provide detailed design guidelines on issues such as component selection and the physical layout of the circuit – all of which should help make sure that you end up with a working circuit.

Example driver – the UCC20520

One example of a driver chip is the UCC20520 4A, 6A, 5.7kV$_{RMS}$ Isolated Dual-Channel Gate Driver with Single Input from Texas Instruments, mentioned in Michael's post. This IC can be used for a half-bridge driver with programmable dead time. The wide supply range for its interface circuitry of 3V to 18V makes it suitable for connection to a wide range of control circuits. The device features isolation from input to output and between the two output channels. It uses a bootstrap approach to generating the voltage for the high-side transistor gate control.

Fig.7 shows a typical application circuit for the UCC20520 (from the datasheet), but simplified to focus on the connection between the driver and the MOSFETs, which are connected in a half-bridge. Output channel A (VDDA, VSSA and OUTA) is configured as a bootstrapped high-side driver for the upper N-channel MOSFET.

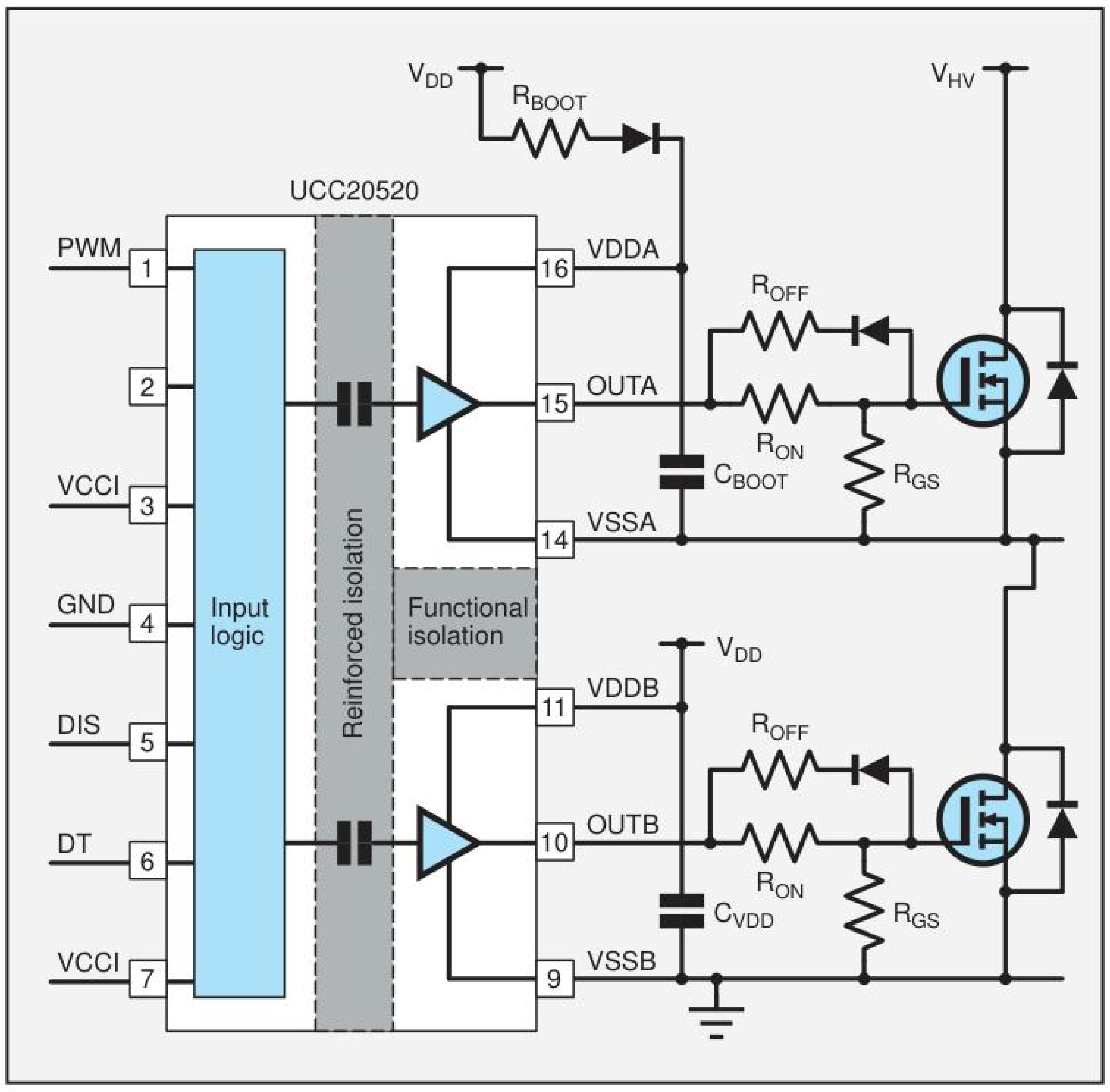


Fig.7. Simplified application schematic for the UCC20520 MOSFET driver (based on Texas Instruments data sheet).

Output channel B is a low-side driver for the lower N-channel MOSFET. Both drivers use the same supply voltage (V_{DD}), with the bootstrap circuit shifting this voltage to be relative to the high voltage load supply (V_{HV}). The input logic has a separate supply voltage (V_{CCI}) via the VCCI pins.

The bootstrap circuit in Fig.7 comprises R_{BOOT}, D_{BOOT} and C_{BOOT}. The circuit is aimed at pulse-width modulation (PWM) operations in which the output is rapidly and continuously switching, it is not suitable for designs where the MOSFETs need to be held in the same state for long or arbitrary periods. For simplicity, in the following discussion we assume there is 0V across the MOSFETS when they are on. Thus, when the low-side MOSFET is on, the source of the (currently off) high-side MOSFET and the VSS power connection of the channel A output circuit (VSSA pin) will be at ground (0V). Under these conditions D_{BOOT} will be forward biased and C_{BOOT} will charge towards V_{DD} via R_{BOOT} and D_{BOOT}. The resistor is used to prevent excessive current flow when the capacitor starts to charge.

When the transistors switch over, so that the high-side MOSFET is on, the VSSA pin will be at the load supply voltage (V_{HV}). D_{BOOT} will be reverse biased as V_{DD} is much lower the V_{HV}. C_{BOOT} will have retained its charge, at a voltage of around V_{DD} (minus the forward drop of D_{BOOT}). The positive supply for the channel A output circuit will therefore be at about $V_{HV} + V_{DD}$, enabling its output (OUTA pin) to provide this voltage to the gate of the high-side MOSFET. This requires V_{DD} to be large enough to provide a gate-source voltage which is sufficiently large to fully turn on the high-side MOSFET. There is also a requirement that C_{BOOT} stores sufficient energy to supply the channel A output circuit and MOSFET drive current for the duration of the switching cycle when the high-side switch is ON. The recommended range for V_{DD} is from 9.2V to 25V. The UCC20520 has an undervoltage lock out feature, which prevents operation if V_{DD} is too low.

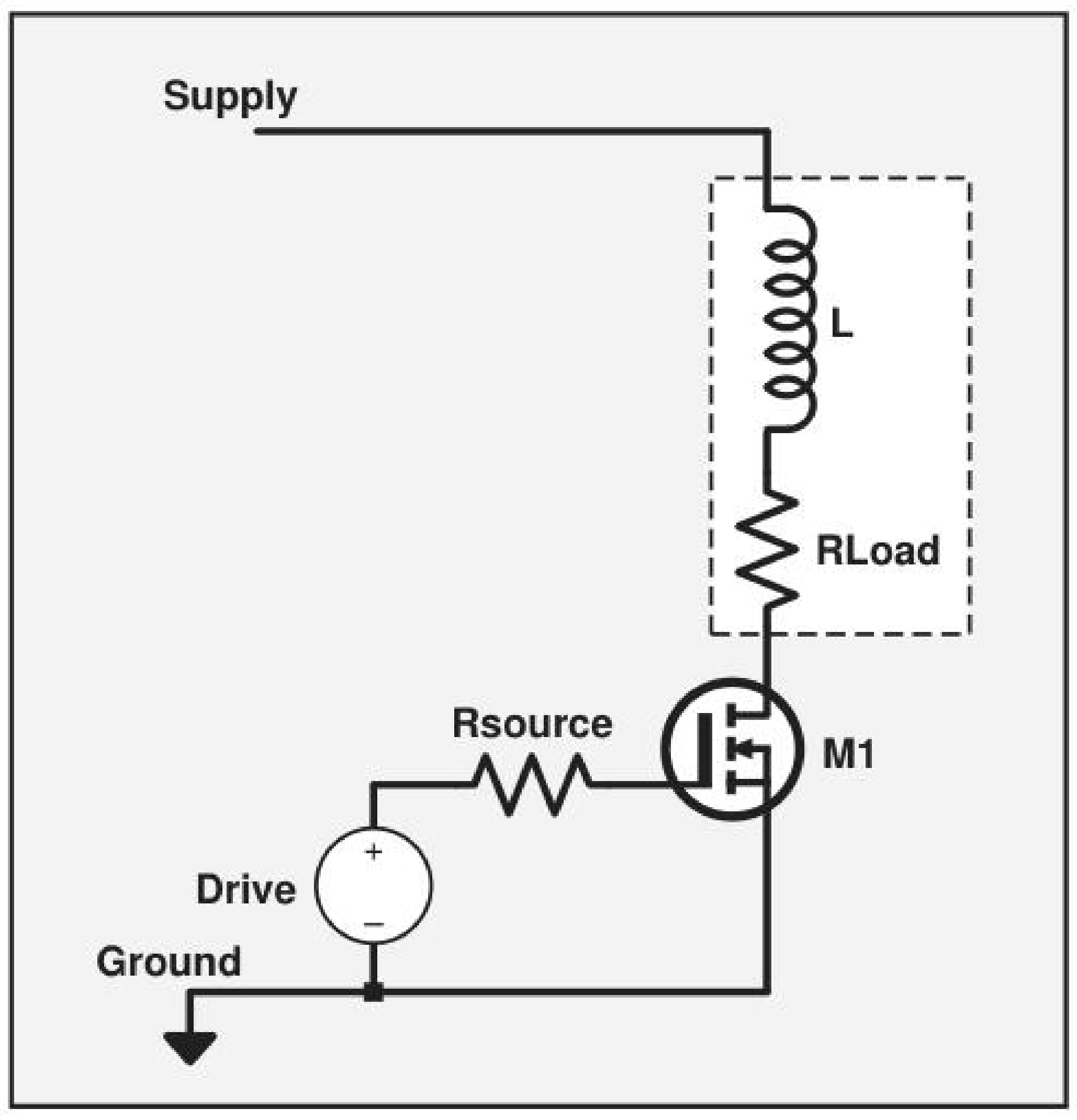


Fig.8. MOSFET switching an inductive load.

Looking at the other components in the drive circuit, we note that the capacitor between the supplies of the low-side driver (VDDB and VSSB pins) is simply a supply decoupling capacitor. No special arrangements are required to power the low-side driver as long as V_{DD} is sufficient to turn on the MOSFET, as already stated for the high-side circuit. The resistors R_{ON} and R_{OFF} help to prevent the ringing that has a tendency to occur in high-speed switching circuits, and provides control over the drive strength, limiting the peak current between the driver output and MOSFET gate. The diode connected to R_{OFF} allows the currents for turn-off and turn-on to be set to different values. Refining the switching in this way also reduces the EMI produced by the circuit. The gate-source resistors (R_{GS}) are gate pull-down resistors, which ensure that the MOSFETs are off when they are not being driven. The 45-page data sheet for the UCC20520 IC provides details on how to calculate most of the component values discussed here, as well many other design parameters which we have not covered.

Inductive loads

While on the subject of MOSFET power switches, it is worth pointing out that a well-known potential cause of power transistor failure is the excessive drain-source

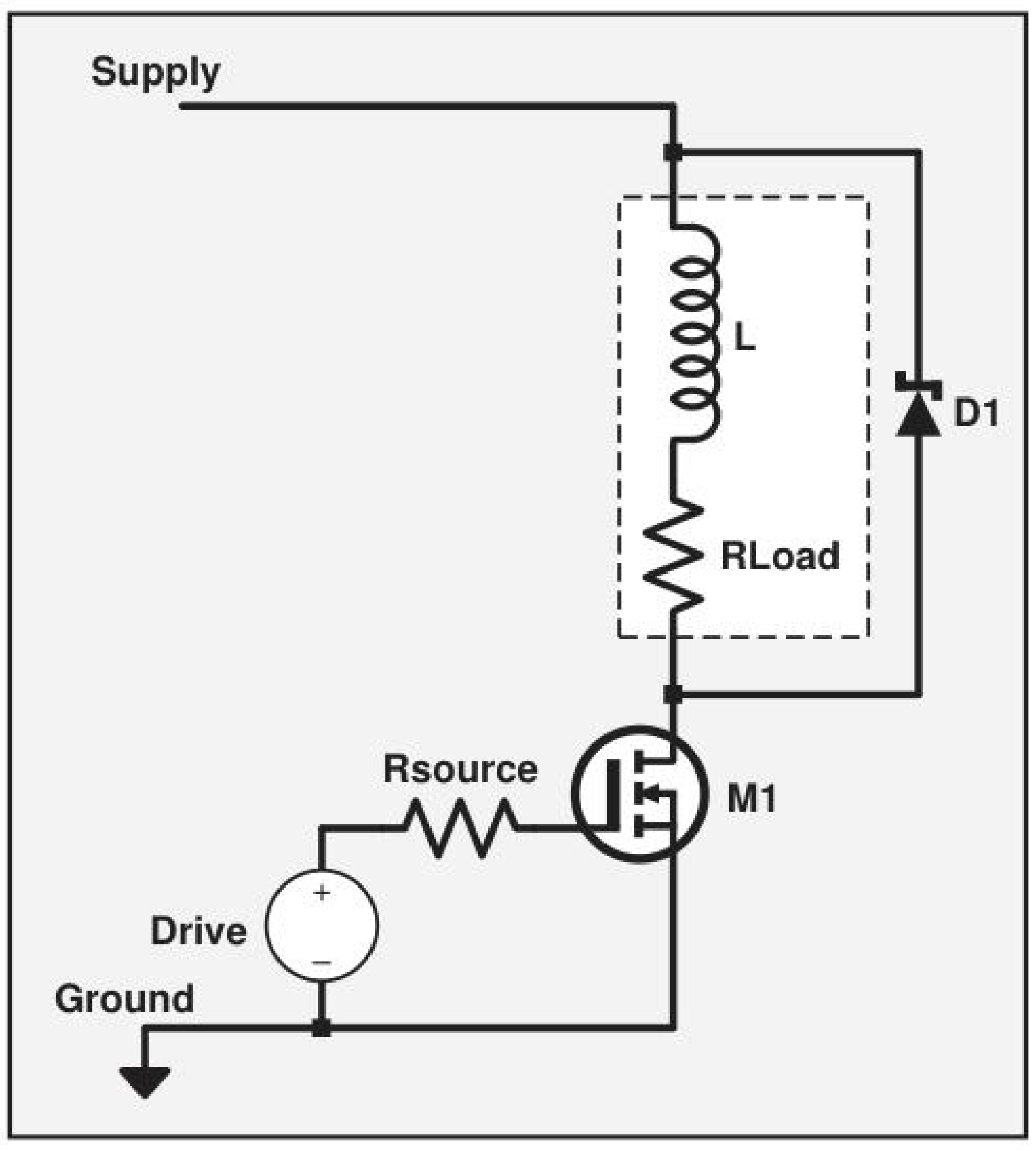


Fig.9. Adding a protection diode to the circuit in Fig.8.

voltage which can occur when switching inductive loads, such as relays, solenoids and motors. A basic scenario is illustrated in Fig.8, in which the load is primarily an inductor (L) but which realistically has some resistance too (R_{Load}) When current in an inductive load is switched off, the magnetic field, which had been established by the supplied current, collapses, inducing a voltage known as the 'back EMF', or 'inductive kick'. This may result in voltages large enough to damage or destroy the MOSFET. The more rapid the change in current as the inductor is switched off, and the larger the inductance, the greater the back EMF generated.

The usual method of preventing the back EMF from causing problems is to place a protection diode across the inductor, as shown in Fig.9 (D1). This diode is reverse biased when the power-switching device is on, but is forward biased by the back EMF; so the diode dissipates the power or feeds it back to the power supply. The protection diode must have sufficient switching speed and power handling to cope with the energy from the back EMF.

Fig.10 shows some LTspice simulated waveforms from circuits like those in Fig.8 and Fig.9. The circuits were simulated at the same time and driven from the same pulse voltage source to facilitate comparisons. The specific components and values are not important here – they will vary significantly in different applications – it is the general shapes of the waveforms which are of interest. The first waveform is the drive signal, which is switching the device from on to off in the waveform shown.

In the second waveform, we see the back EMF, the voltage spike produced by the inductor when it is switched off by the MOSFET (this is the waveform for the circuit in Fig.8). In this case it is around 20V (four times the supply voltage), but can easily be much larger in real applications. The simulation was set up to keep the spike reasonably small so that the final drain voltage could easily been seen on the graph. The back EMF appears as a positive voltage spike at the drain of the MOSFET. If this voltage is large enough, it will cause breakdown to occur in the transistor and high current will flow, possibly damaging the device.

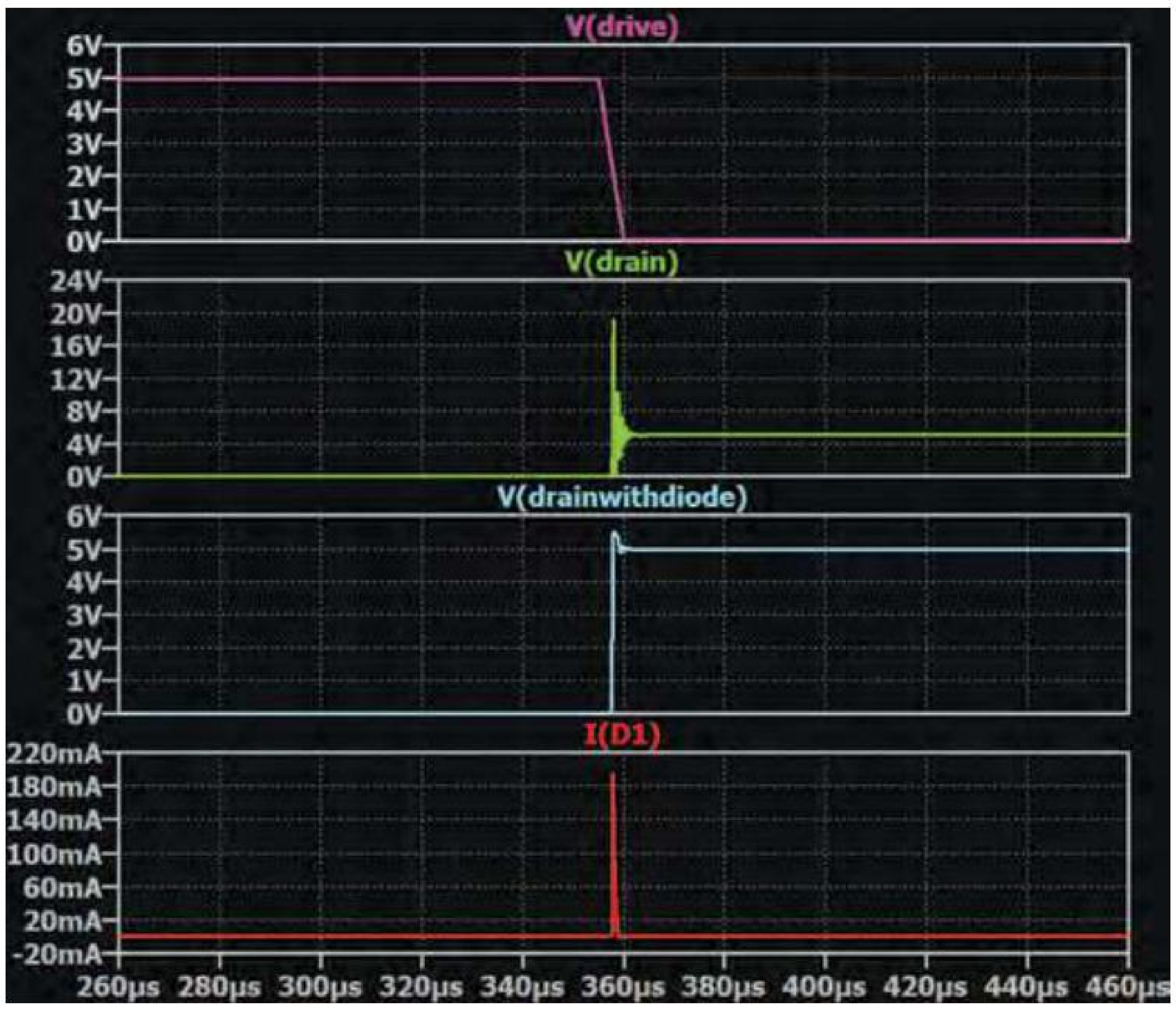


Fig.10. Illustrative waveforms in for the circuits in Fig.8 and Fig.9.

The third waveform in Fig.10 shows the same circuit, supply and input drive conditions, but with a protection diode in place, as shown in Fig.9. When the back EMF occurs, a small overvoltage of around 1V appears at the drain – the turn on voltage of the diode.

The fourth and final final waveform in Fig.10 shows the diode current, which indicates when it is conducting to suppress the back EMF spike.

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PIC n' Mix

Mike Hibbett's column for PIC project enlightenment and related topics

Designing PCBs with EagleCAD – Part 2

This month, we return to the topic of getting boards professionally manufactured for your own projects, a task that requires the use of a PCB CAD (computer-aided drawing) program to specify your board design and then generating the files required by PCB manufacturers to turn your design into reality. In the past, this process was very complicated, and PCB manufacturers were not very accommodating towards hobbyists. Now, with the Internet providing global communication, automated purchase systems and secure payment services, PCB manufacturers find it easier to engage with non-professional users around the globe, even for very small quantity orders. Some manufacturers operate 24-hour facilities, so you can order your board in the middle of the night – yours or theirs!

PCB CAD programs

There are several PCB CAD programs available on the market, many of them extremely expensive. This cost is justified for complex commercial product development where a professional engineer's time is valuable, and production mistakes costly. Altium Designer and PADS from Mentor Graphics fall into that category. At the other end of the spectrum you have less fully featured tools such as EagleCAD from CADSoft (now owned by AutoDesk), which has low-cost licences for simple commercial use, and free (but limited functionality) for hobbyist use.

The free version of EagleCAD is limited to board designs with an area not exceeding 80cm^2 – more than enough for many hobbyist projects. The author has a standard paid-for licence, and the €130 yearly cost is justified by doing part-time professional projects (including *PIC n' Mix* articles, which would be considered commercial use.)

An alternative to EagleCAD is the completely free system called KiCAD, a suite of programs designed by a community of developers who not only release the software for free, but also make all the source code for the system free too. In operation, the two programs are similar, as can be seen from Fig.1 and Fig.2.

KiCAD has a steeper learning curve than EagleCAD but has significantly more features – including unlimited board sizes. KiCAD provides 3D rendering of your PCB design with the components fitted, and you can even integrate your PCB design into your enclosure design, if you have the 3D data for it. An example 3D view is shown in Fig.3.

One of the most time-consuming activities when designing a PCB is having to deal with unusual components – especially connectors – for which existing library components have not been created. All components must have two symbols created; one for the schematic diagram, and another for the PCB. The PCB symbol is very complex as its physical model must *exactly* match that of the real component, as we'll see later. EagleCAD provides excellent tools for creating new library components, but using a library part definition off-the-shelf can save hours of effort. This is where EagleCAD excels; the company provides a large component library as part of the installation package, but also many companies and individuals provide EagleCAD libraries for free download, so quite often you can find your components available on-line.

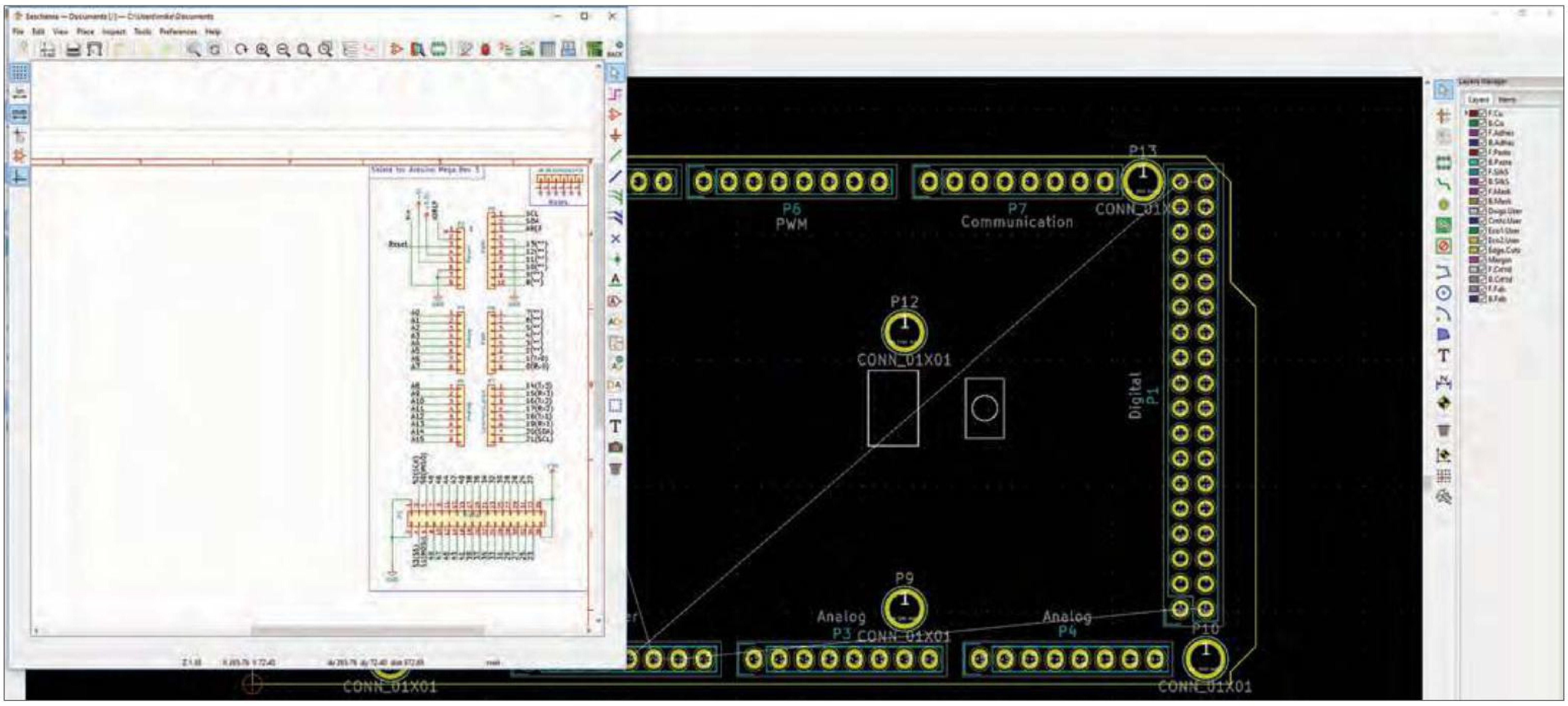

Fig.1 KiCAD user Interface

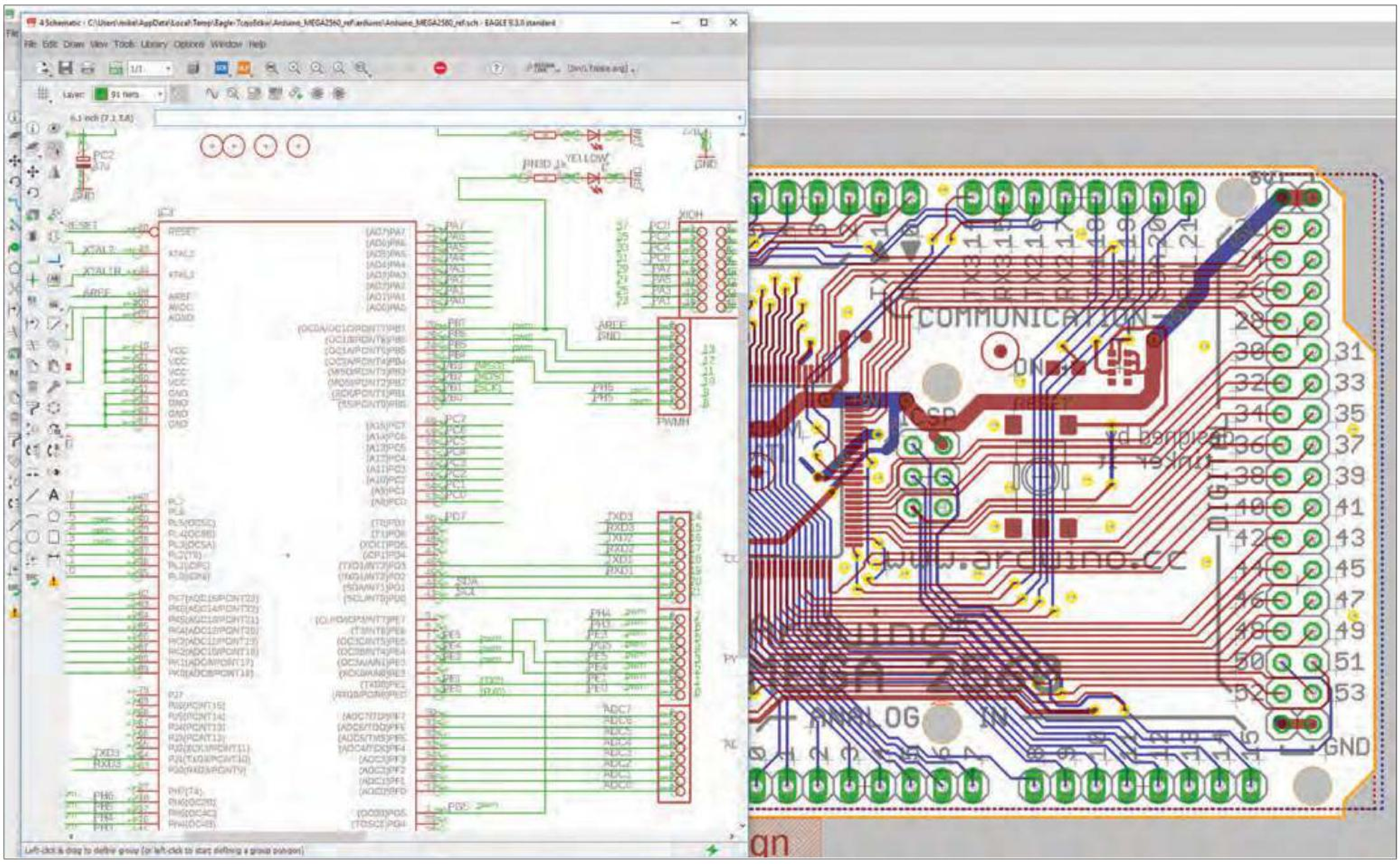
Fig.2 EagleCAD user Interface

It's because of this large component library and the general popularity of EagleCAD in the community that we at *PIC n' Mix* have standardised on its use. If you are new to PCB CAD, we recommend starting out with EagleCAD. If you outgrow it, perhaps due to the limitations of maximum board dimensions available in the free licence version, then consider moving over to KiCAD.

KiCAD is being developed, enhanced and new component libraries added year on year, so it's quite possible that in the future KiCAD may become the default choice for beginners. For now, however, we recommend starting out with EagleCAD.

Installation

Installing the free version of EagleCAD is straightforward on the three major computing platforms: Windows, Linux and MacOS. You can download the free version of the product here: **http://bit.ly/pe-apr19-auto**

Installation is straightforward, with the only issue being the first time you run Eagle after installation you must be connected to the Internet so that the program can verify your username and password for your account. A minor annoyance, but annoying all the same, as it should be unnecessary.

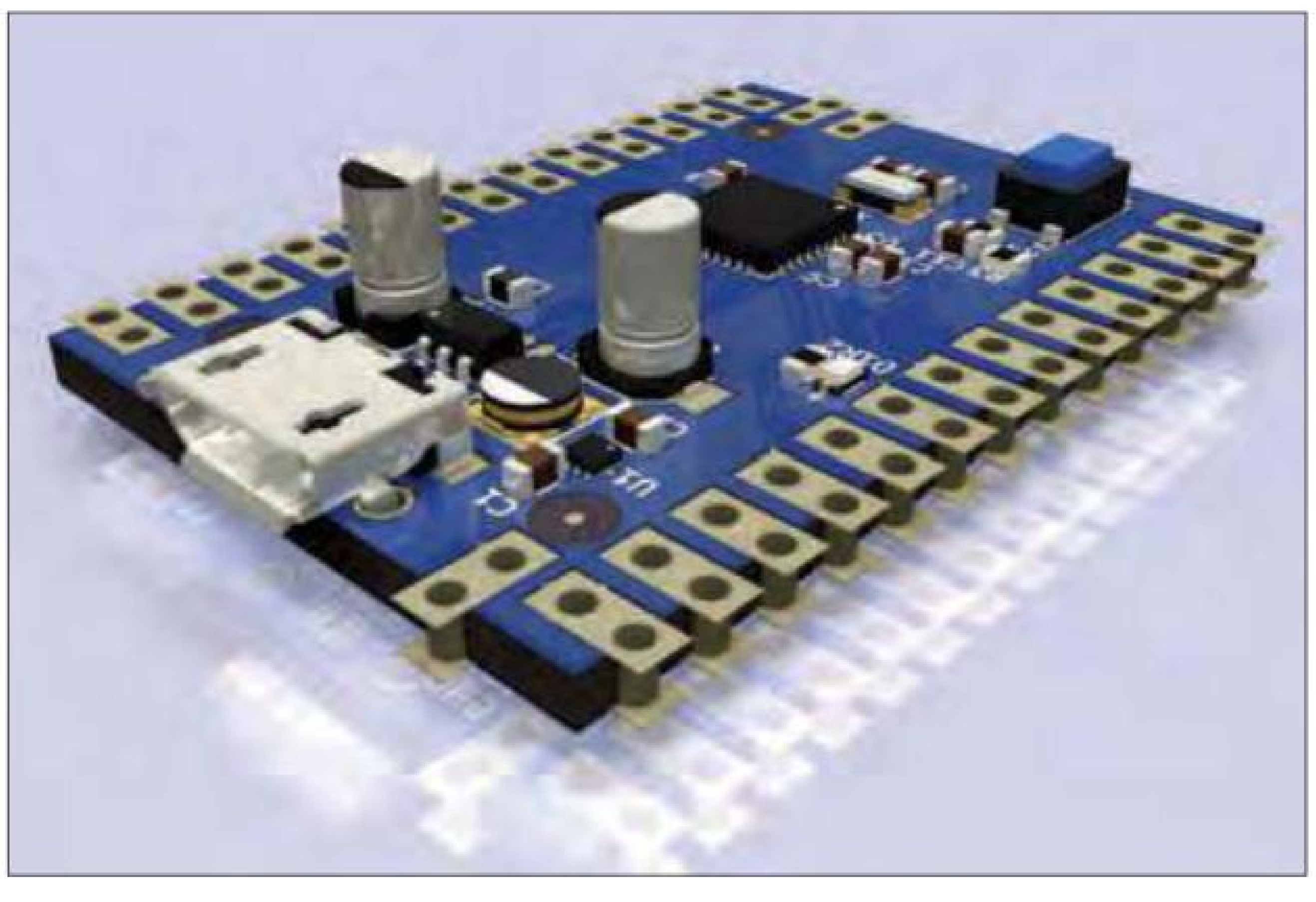
Fig.3 3D PCB view

PCB basics

Before talking about CAD design techniques, let's discuss what we are designing – a printed circuit board. Even before drawing the schematic, it's good to think about the construction and shape of your PCB, as it influences what connectors you use, whether switches and indicators will be mounted on the PCB or wired to it, and so on.

PCBs can be manufactured from many materials with many layers, but for hobbyists the typical base material is FR4 (a flame-retardant glass-reinforced epoxy material) with one or two conductive layers, on the top and bottom surface. Most manufacturers' factories are optimised for double-sided PCB manufacturing, so you are unlikely to save any money constraining yourself to a single-sided design. The FR4 base material comes in different thicknesses, but the usual default thickness of 1.6mm gives excellent board stability and is the cheapest option.

The copper layer is glued to the surface of the FR4 and will be selectively etched away to the pattern specified in your design. On top of the copper layer is a solder-resist coating. This is a layer that provides a protective coating to the copper, and actively repels molten soldering during the soldering process. Again, this coating is placed selectively based on your design, but its shape is automatically generated for you by the CAD program. You typically have a choice of colour for this coating.

On top of the solder-resist layer comes the silkscreen layer. This is a single-coloured print (again, you can choose the colour) which you add to your design as you see fit. Some details, such as component outline and component numbering are added automatically, but you are free to add any other text (such as product name) or even bit-mapped images, such as company logos. Finally, a surface finish process is applied to coat any exposed copper, typically the solder pad positions of components and connectors. There are several surfaces finishes available, including gold plating (which isn't as expensive as it sounds, as the layer is only a few microns thick.) The cheapest (and the default) finish is

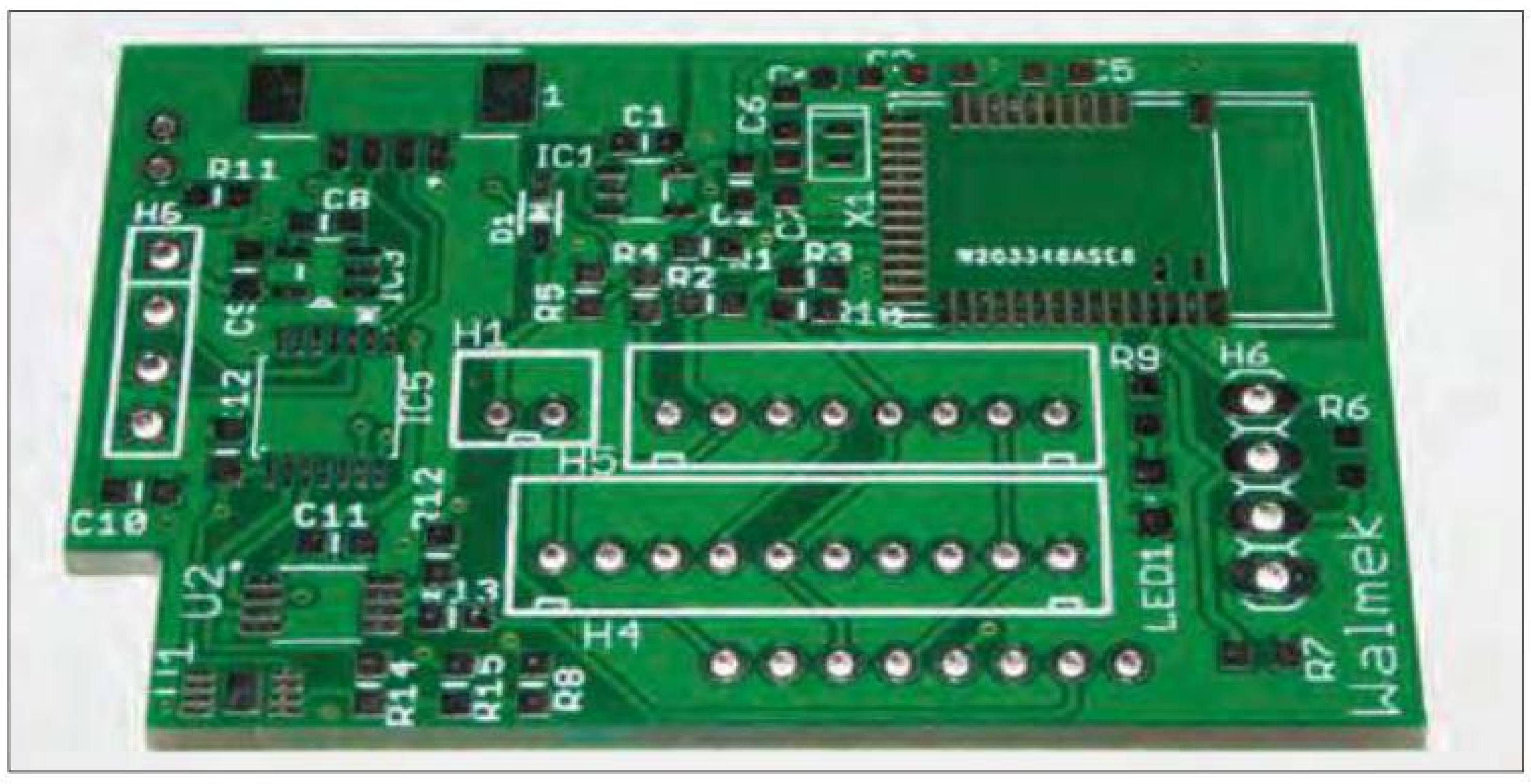

Fig.4 A routed PCB design

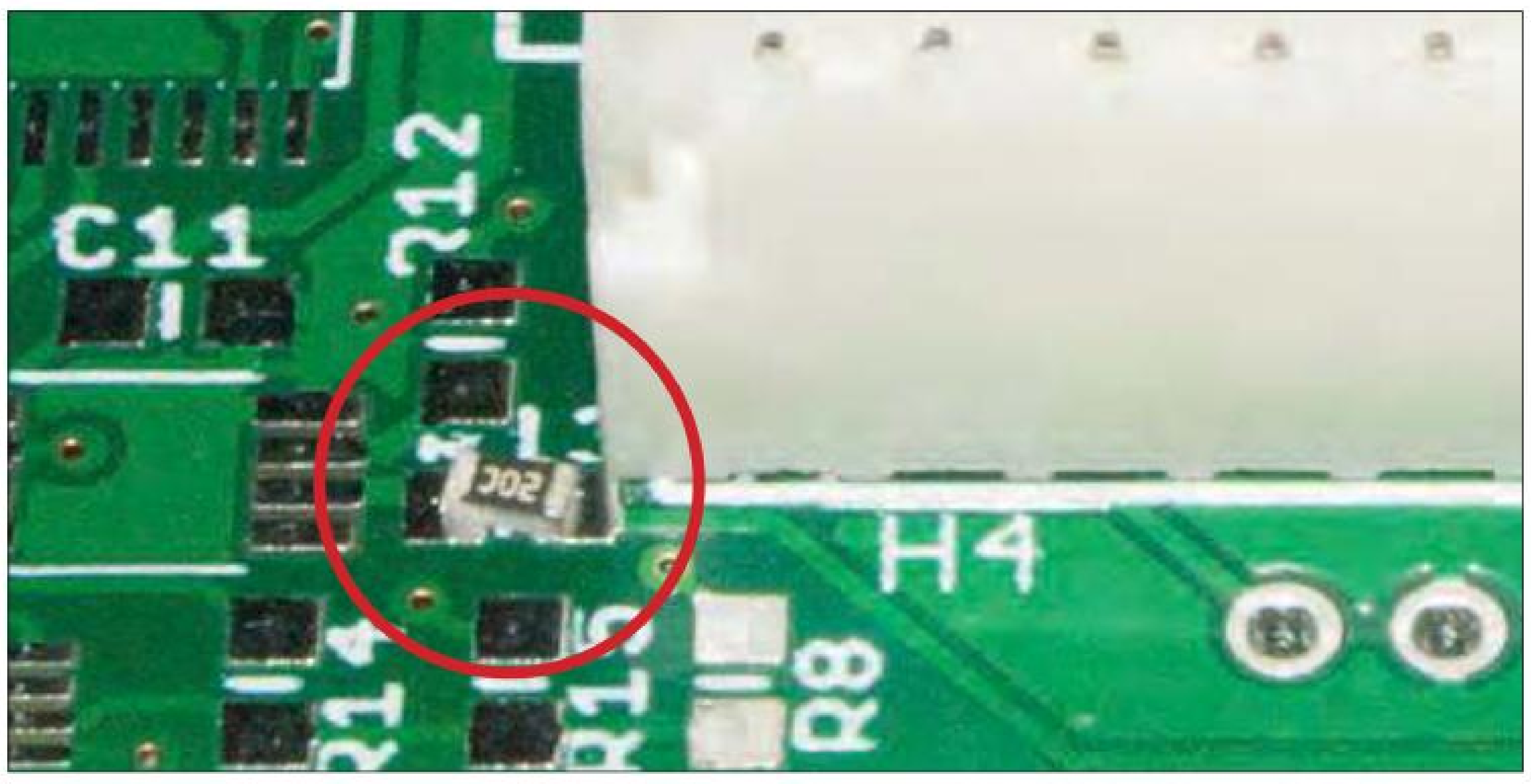

Fig.5 Poorly spaced components

HASL (hot air surface levelling), which coats the exposed copper with a thin layer of solder, followed by a blast of hot air to leave the surface relatively flat. This layer process is identical for both the bottom and the top of the PCB.

Drilling, milling and printing

When thinking about the design of a PCB it's helpful to consider the PCB manufacturer as a company with big sheets of copper clad PCB boards, with drilling machines, milling machines and ink printing machines. You specify what sized holes go where, what milling operations will be made, what the various print layers will be in the CAD program, and then your output files form the input to the automated drilling, milling and printing machines within the factory. It is because all these steps are performed by machines, not people, that the costs for PCB manufacture have fallen so low over the years, as companies invest in more automation equipment and connect them together efficiently.

As a result of this automation, drilling holes and routing complex edges in your boards adds no extra costs; the machines are there anyway, and your boards will pass through those machines in the process, whether you use them or not. Extra component pads, even 0.1-inch plated through holes as found on Veroboard can be added at no cost – giving you the flexibility to re-use a PCB for other uses, or even add prototyping regions. If you are not in a hurry, take the time to make use of any vacant board space in your design.

Complex board outlines can be specified to allow fitting the board into an existing, off-the-shelf enclosure. PCB-mounting battery connections can be added to allow the batteries to sit securely on the PCB, and even strain-relief holes drilled, which allow cables to be routed safely through the board.

Design flow

When creating a PCB, the steps that you take within the CAD program are as follows:

- Draw your schematic
- Decide on number of PCB layers
- Define PCB outline
- Place components where desired
- Route signals between components
- Validate your design
- Generate PCB files (Gerber files)

To place an order for a PCB, you visit the website of your chosen PCB manufacturer and select their 'instant quote' page – most have this capability now.

At this point, you specify some basic information about your design: its length and width, the number of layers, and how many boards you want. There may also be an option for how quickly you want them built. PCBWay offers a 2-to-3-day service by default, or 24 hours, at a higher cost. Typically, all other process options can be left at default.

Normally at this point you will be quoted a price. The quotation is automatically generated, which means you can easily experiment with other options, such as build time or different surface finishes to see the impact on cost. Once happy you can upload your zip file, and within a few hours receive a confirmation that the files have passed review. You can now pay online, and wait for your boards.

Design validation

All CAD programs provide tools for validating your design. There are two stages to this. ERC (Electrical Rules Check) which makes sure that all components are connected to something, which is a vital check as it is possible to connect wires close to a terminating point, but not quite make a connection. This validation is performed on your schematic. DRC (Design Rules Check) is a more complex set of tests, which run against your PCB design. DRC validates that no signals cross over or touch each other (yes, it is possible to do this. It's up to you where you route signals!) and that the gap between signals or features is not too small. All PCB manufacturing machines have accuracy limits, and DRC checks your design against those limits. EagleCAD's default set of rules work well and covers most manufacturers default limits. Some manufacturers even provide their own DRC rules file that can be downloaded and used by EagleCAD, but we have not found that to be necessary. If your design really must have very thin tracks or tiny holes drilled, you can do this, but you will be required to pay a higher fee.

The two views of your design, the schematic and the PCB layout, remain consistent with each other as you evolve or change the design. If you add a new component to the schematic, the outline of it will appear in the PCB view, ready for you to re-position and route in. If you delete a component it will disappear from the PCB view – but any tracks you have routed to it remain and need to be deleted manually.

Auto-router

All modern PCB CAD tools provide an automatic signal routing capability. This performs an incredible task of working out the most efficient way to route all the signals between all your components, resulting in the simplest, electrically correct wiring of your board. It's a single click option, takes a few seconds, and could save you hours of work. Unfortunately, there is no free lunch. While all the signals may be connected, it is very unlikely that your design will work as well as you wish. High-current paths may not take the shortest route, and the auto-router does not understand the EMC impact of its choices. Designers rarely, if ever, allow the auto-router full control over the process. Instead, a common technique used by PCB designers is to experiment with different component positions, running the auto-router, and looking at the result. Did moving some components result in fewer vias being generated? If yes, then that was a good choice of component placement; the auto-router's work is then discarded, and the signals manually routed. For hobbyists, manually routing the PCB is part of the fun; holding the final product in your hand and knowing this design was truly yours adds to the satisfaction.

Handling manufacturing data

To demonstrate how easy it is to take a PCB design through to a manufacturer we have created a YouTube video to demonstrate the process. You can view it at: **https://youtu.be/NGhsPEljgHQ**

A full tutorial on how to use EagleCAD is impractical in a print magazine, but EagleCAD's popularity means there are many animated and video-based tutorials on the Internet. One excellent series is hosted by Sparkfun and can be found here: **http://bit.ly/pe-Apr19-pcb**

We recommend looking at several tutorials as there is always a chance to learn something new, or you may find that a different presentation on a confusing topic helps clarify it. In the end, however, there is no better learning technique than building something and discovering your mistakes. With the availability of very low-cost PCB manufacturing services, these mistakes do not need to be expensive.

Even seasoned PCB designers make mistakes. In Fig.4 you can see a PCB, which passed all design and engineering rules checks, was approved by the manufacturer and looks fine (a few silkscreen component indicators have been truncated, but this was considered acceptable.) When it came to assembly, however, it was found that the 10-pin connector did not physically match the outline shown in the silkscreen – resulting in one corner touching the pad of a resistor, as can be seen in Fig.5. It was possible to deal with this when hand assembling the boards, but a commercial PCB assembly company would reject it. This issue was caused by the component library for the connector being incorrectly designed. The moral of the story is, always build a small quantity of boards before committing to a large production build!

There are many PCB manufacturers available to hobbyists around the globe now, and in our opinion one that leads the field in terms of quality, ease of use, service and price is the Chinese manufacturer 'pcbway.com'. As an example, they will produce ten double-sided boards measuring 100mm x 100mm for just US$5, with delivery costing from US$10 for slow postal service up to US$25 for three-day Express DHL. You can design a PCB one weekend and have it in your hand the following Friday, all for less than £24.

One thing to note, depending on where you live, you may be subjected to import tax duties if you use a courier delivery service; we find that around one order in three gets 'selected' for taxation, and in our experience this can amount to an additional 40% charge. Orders delivered by China Post have never been subjected to customs duties (again, in our experience). If you live in a country that has an affordable PCB manufacturing service, then it's worth comparing the manufacturing fees plus delivery charges between several suppliers.

Next month

Next month we start to explore the versatility of Microchip's cheapest and tiniest microcontroller, the PIC10F200 series. With just eight pins and availability in easily breadboarded packages we will have fun discovering what projects we can dream up for it – and build them. These devices are readily available from all major suppliers, costing just £0.40 each. As delivery charges may be significantly higher than the cost of the device itself, it's worth looking around at other component suppliers, such as those who advertise in the magazine, or adding some to a larger component order. The article series will cover several different projects using a range of components. If you have any suggestions for a project idea, why not share it on the forum: **www.eeweb.com/forum/category/epe-magazine**

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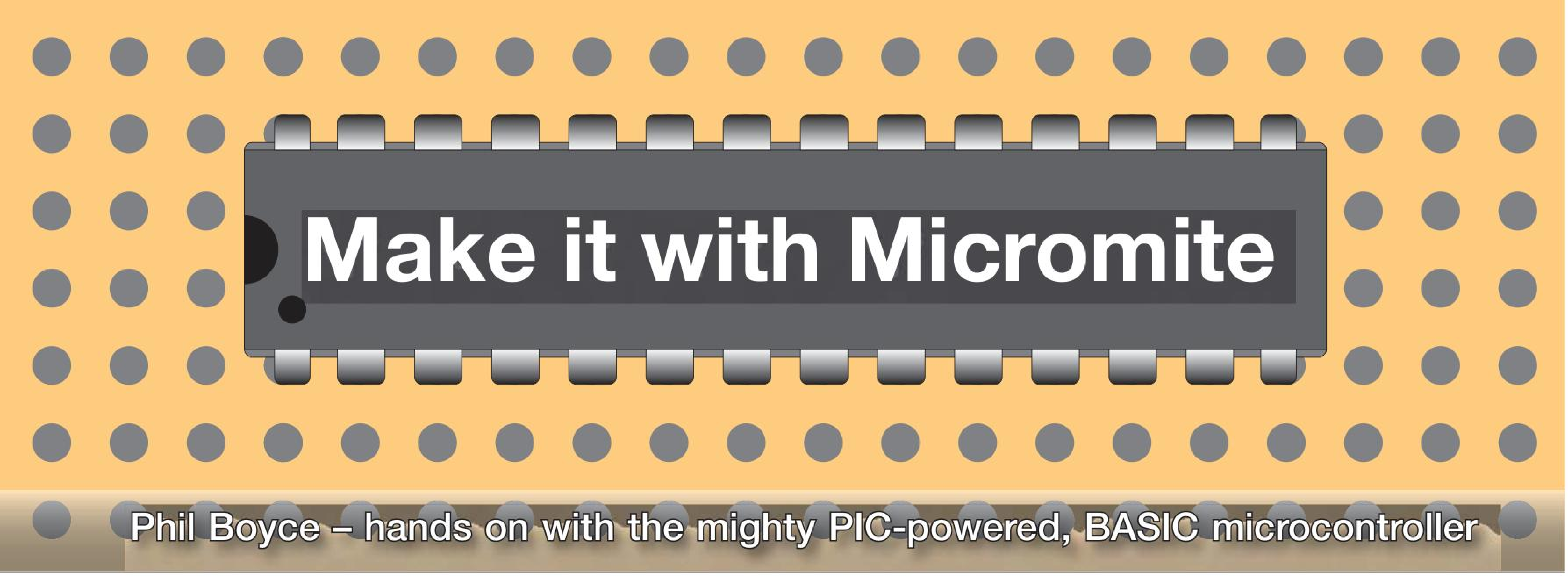


Make it with Micromite

Phil Boyce – hands on with the mighty PIC-powered, BASIC microcontroller

Part 3: Building the Micromite Development Module

Over the last two issues we introduced the Micromite and built a *Micromite Keyring Computer* (*MKC*). This month, we will build the accompanying *Development Module* (*DM*), which allows us to configure and program the *MKC* for all the different projects and applications that we will be describing over the coming months.

Development Module

The core function of the *DM* is to enable us to connect a computer to the *MKC*. It then allows you to write, develop and edit your code, which is contained within the *MKC* itself. It has been designed to simply plug into the *MKC* when developing code, and then it is removed once the code performs as required. It also has the functionality to update the MMBASIC firmware as and when new releases are available, meaning there is no requirement for a third-party PIC programmer such as a PICkit 3.

DM circuit description

The circuit diagram for the *DM* is shown in Fig.1. Just like the *MKC*, it is a very simple circuit thanks to a dedicated 14-pin PIC microcontroller – the 'MicroBridge' – that contains all the intelligence. The circuit essentially comprises a voltage regulator (identical to that in the *MKC*), the MicroBridge IC, two buttons (switches), several rows of sockets and pins (to provide connectivity to the *MKC* and the 'outside world'), and the usual small quantity of other, mostly passive components.

The *DM* requires a 5V input, supplied via J6 when it is plugged into a powered *MKC*. This 5V input feeds into the voltage regulator (IC2) which in turn provides the required 3.3V output to the MicroBridge (IC1). Two 10µF tantalum capacitors (C1 and C2) provide the necessary input and output voltage smoothing.

The green Power LED (D2) is also fed from the 5V input. Current-limiting resistor R9 protects the LED.

The 'Mode' button (S2) toggles between the two available MicroBridge modes. On power up, the MicroBridge defaults to 'Comms' mode. This means the *DM* acts as a USB-to-serial module allowing a connected computer to communicate with the Micromite via the TxO and RxI Console pins discussed in *Part 1*. These two Console connections from the *MKC* enter the *DM* via pin strip J11. Resistors R6 and R7 provide a level of protection to the MicroBridge if an external voltage is applied to these points on socket J10.

R5 is a pull-up resistor on the MicroBridge's serial Rx pin and prevents any noise feeding into the MicroBridge when plugging in the *DM*. R4 is a pull-up resistor for the Mode button (S2) enabling accurate detection of button presses.

When the MicroBridge is in 'Comms' mode, the red Mode LED (D1) is off. If the Mode button is pressed, it will then toggle the MicroBridge into 'Firmware Update' mode – indicated by the red LED (D1) turning on. R8 is D1's current-limiting resistor.

In 'Firmware-Update' mode, it is possible to update MMBASIC to a newer version by using a Windows application **Pic32Prog.exe** – this will be covered in detail later in the series. This is achieved via a single USB lead connecting the *MKC* to a computer. For the MicroBridge to perform the update, it requires connection to the two USB signals, D+ and D–. These are supplied from the *MKC's* USB Break-out board (BoB) and enter the *DM* via the two pins on J4. There are also three connections required between the MicroBridge and the Micromite to complete the Firmware update. For advanced users, these are the ICSP signals: $\overline{\text{MCLR}}$, PGD, and PDC. These three connections are made via pin strip J11, as indicated in Fig.1. R2 and R3

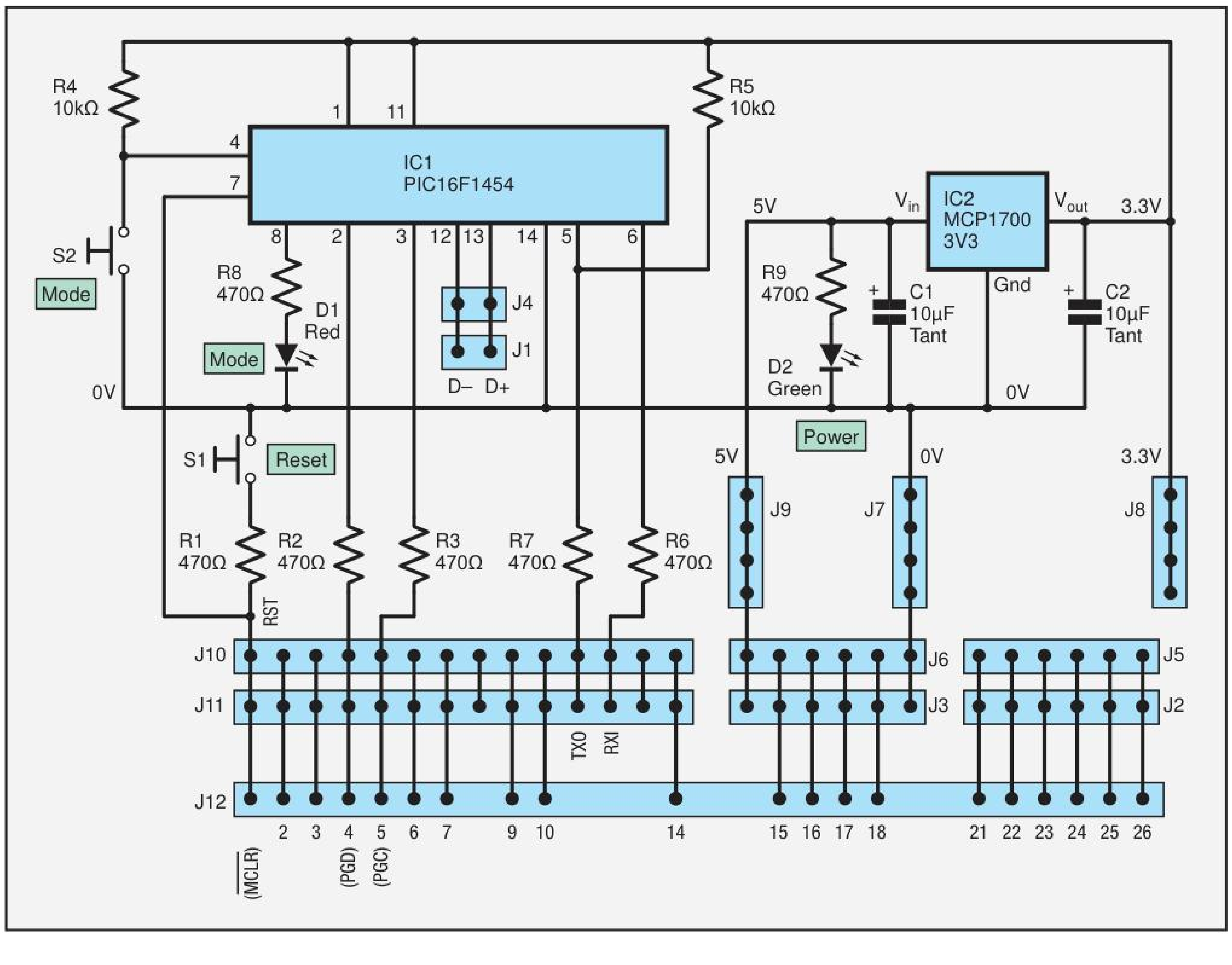


Fig.1. Circuit diagram for the *Development Module* (*DM*).

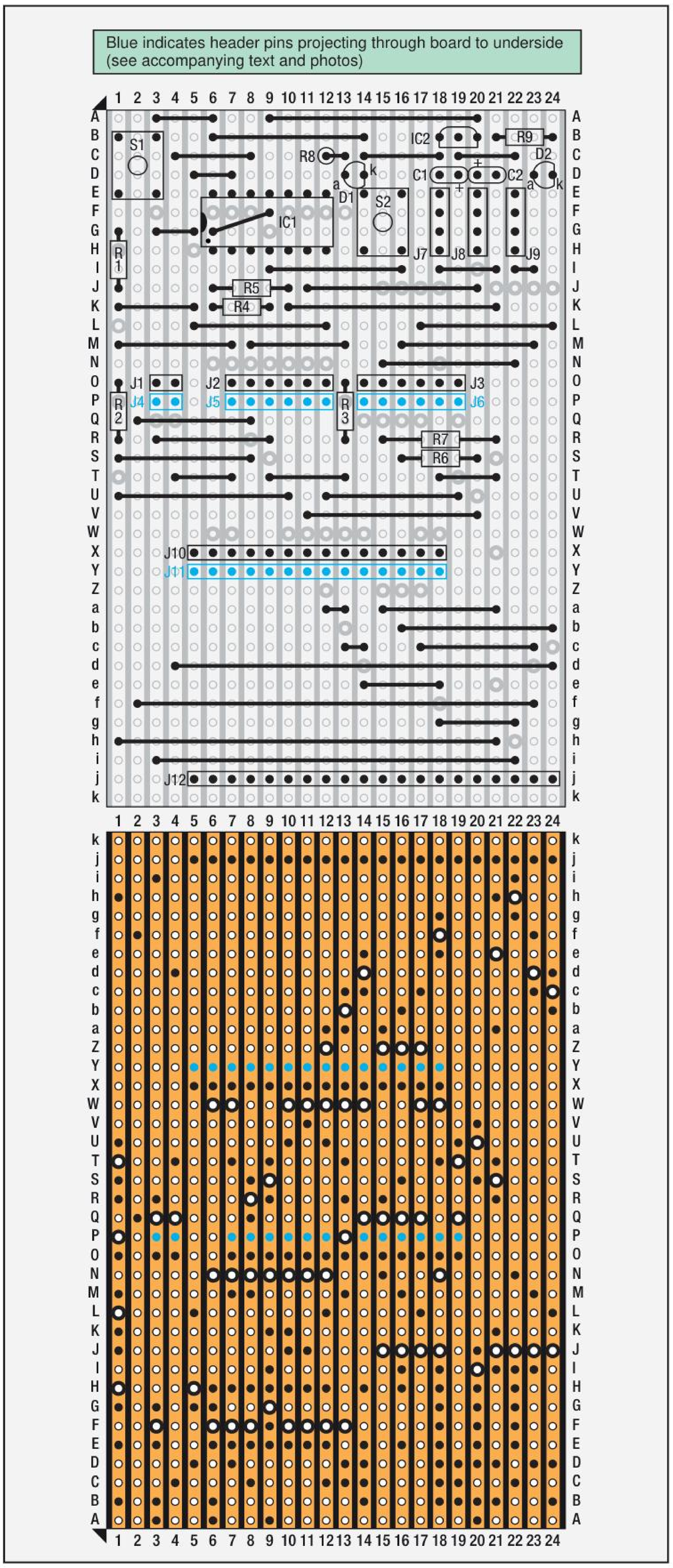

Blue indicates header pins projecting through board to underside (see accompanying text and photos)
S1
S2
IC1
IC2
R1
R2
R3
R4
R5
R6
R7
R8
R9
D1
D2
C1
C2
J1
J2
J3
J4
J5
J6
J7
J8
J9
J10
J11
J12

Fig.2. (Top) Stripboard layout for the *DM*; (below) copper track view showing positions of where to cut tracks. (J12 – see text).

provide protection to the MicroBridge if an external voltage is applied to these points on socket J10.

The Reset button (S1) resets the Micromite – for example, if it gets stuck in a loop. The Reset signal is Pin 1 on the Micromite, and pulsing this pin low (shorting it to 0V) will reset the Micromite. R1 provides a level of protection to the MicroBridge should the Reset button be pressed during a Firmware Update and when there is an external voltage applied to socket J10 on this RST signal.

Three female sockets (J2, J3, and J10) match the *MKC's* three sockets. This allows you to plug external hardware into the *DM* while developing code.

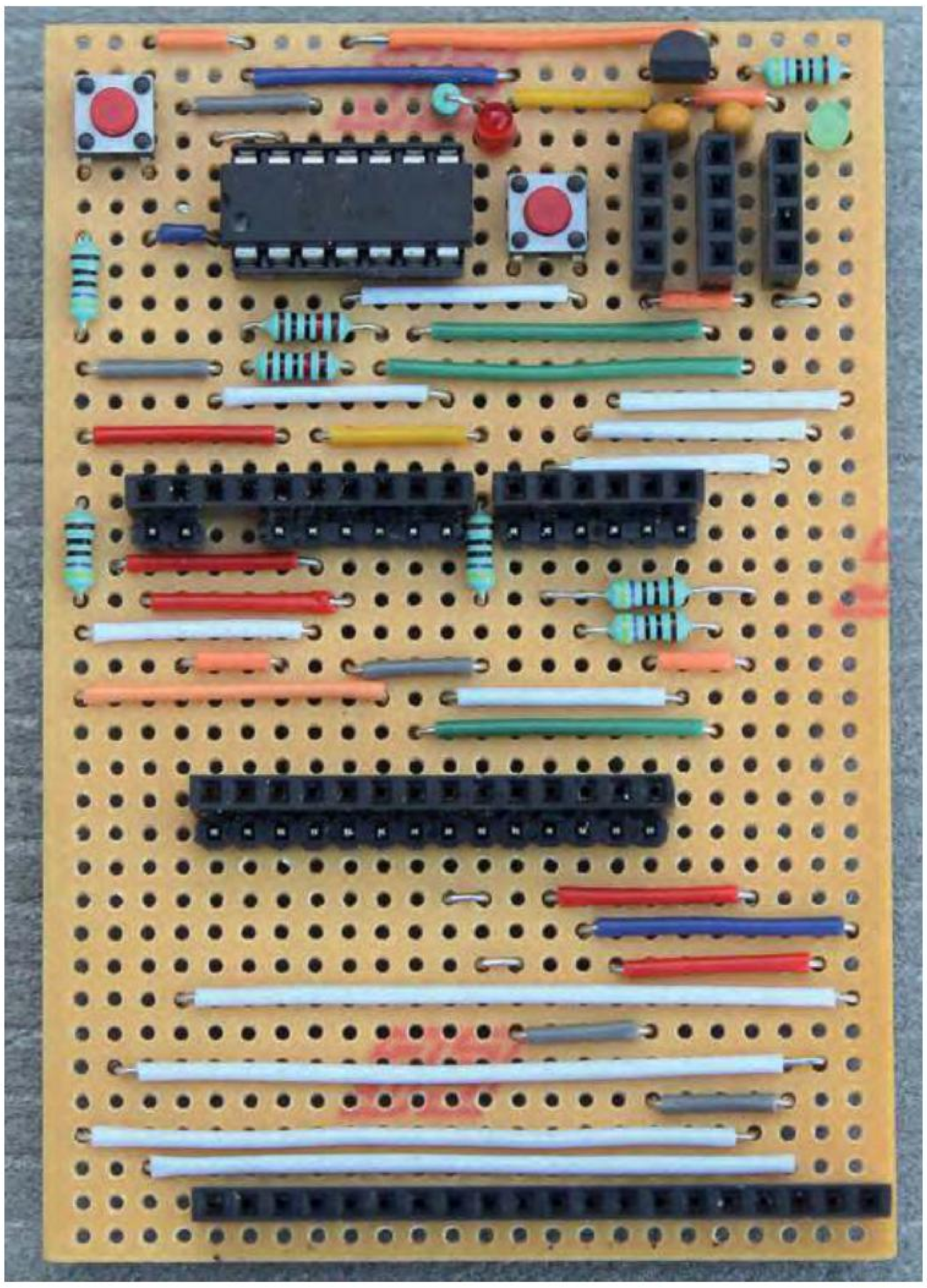


Fig.3. Component side of the assembled stripboard *DM*. In this prototype J1 and J2 are combined – you should build the version shown in Fig.2 (ie, J2 is a separate 6-way socket).

The three 4-way female sockets (J7, J8, J9) provide convenient access to 0V, 3.3V, and 5V rails for powering external hardware. Finally, J12 makes the reset signal, and all 19 I/Os available on a single 20-way connector. This can be either a row of pins (as supplied in the kits) or a 20-way socket. If you use pins, then these could be mounted on either side. For now we recommend leaving J12 unsoldered.

MicroBridge

Before we start construction, first a note about IC1 – the MicroBridge. This is a 14-pin PIC16F1454 chip loaded with the MicroBridge firmware. If you purchased a kit, then the MicroBridge software is already installed. However, if you have purchased your own blank PIC chip, then you will need to load the **Microbridge_firmware_V1.18.hex** file, which is contained in the 'Construction Pack' available for free download from **geoffg.net/microbridge.html**. To program the PIC you will need to use a suitable PIC programmer (such as a PicKit 3); alternatively, a pre-programmed MicroBridge chip is available for £3.75 (+ shipping) from **micromite.org**

DM construction

Even though the *DM* is bigger, and contains many more wire-links, it is actually easier to assemble than the *MKC*. We will not go into as much detail as the *MKC* since the techniques used here for construction are essentially the same. We will simply guide you through, pointing out anything relevant.

Once again, there is a recommended sequence of steps that we advise you to follow in order to help with construction:

1. Prepare the stripboard
2. Install components, starting with the wire links
3. Resistors (R1-R9)

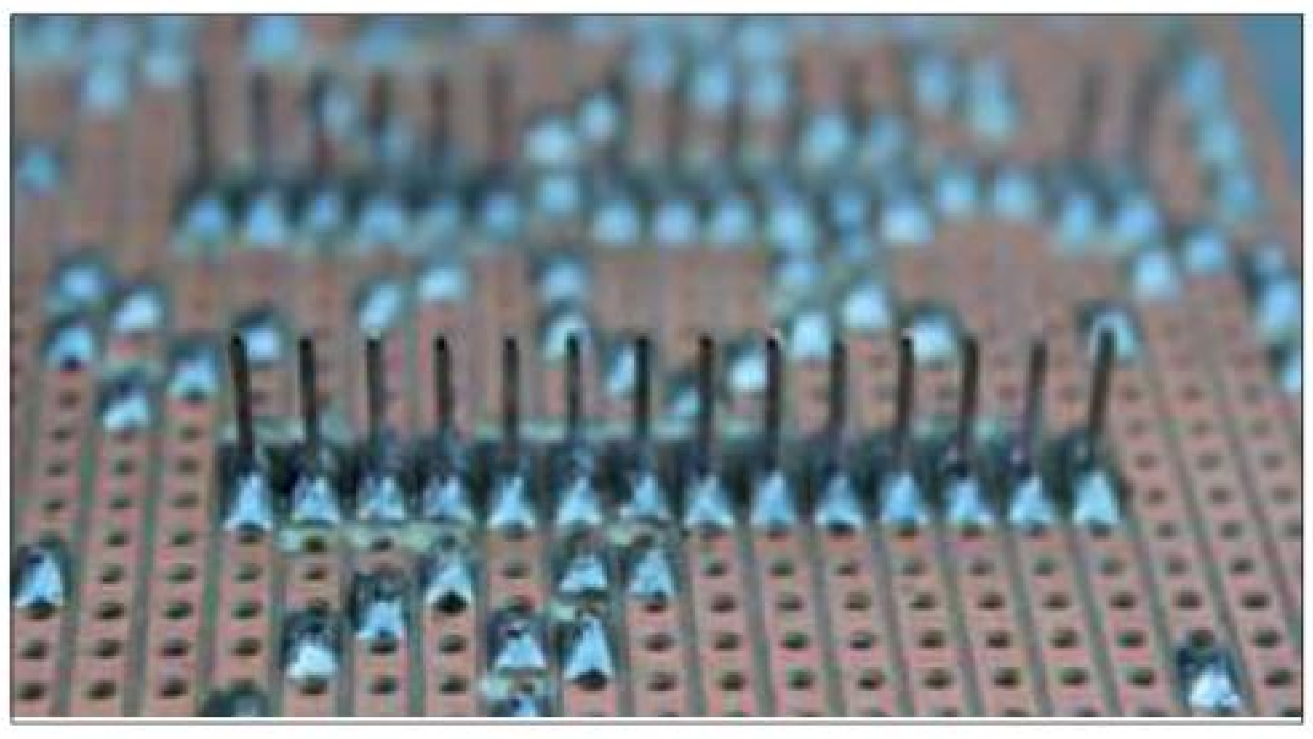


Fig.4. Close up of the underside of the *DM* showing soldered pin strip J11.

4. Capacitors (C1, C2)
5. Buttons (S1, S2)
6. Semiconductors (D1, D2, IC2, IC1 plus socket)
7. Female sockets (J2, J3, J10, J7, J8, J9, J12*)
8. Pin strips (J4, J5, J6, J11, J12*)

Step 1: Preparing the stripboard

The *DM* is built on a piece of stripboard 24 strips wide, with 37 holes per strip. As you can see from Fig.2, there are no corner cut-outs required. If you have purchased your *DM* kit from **micromite.org**, then the stripboard will already be the correct size. However, if you need to obtain the required size from a larger piece of stripboard, simply follow the methods described for the *MKC*.

Next, using a permanent parker, mark out all the 'cut-points' on your stripboard at each location shown in the bottom diagram in Fig.2. Take your time – they need to be 100% accurate. Once you have them correctly marked, then make the cuts.

Use the same techniques mentioned for the *MKC* to check, and finish preparing the *DM* stripboard.

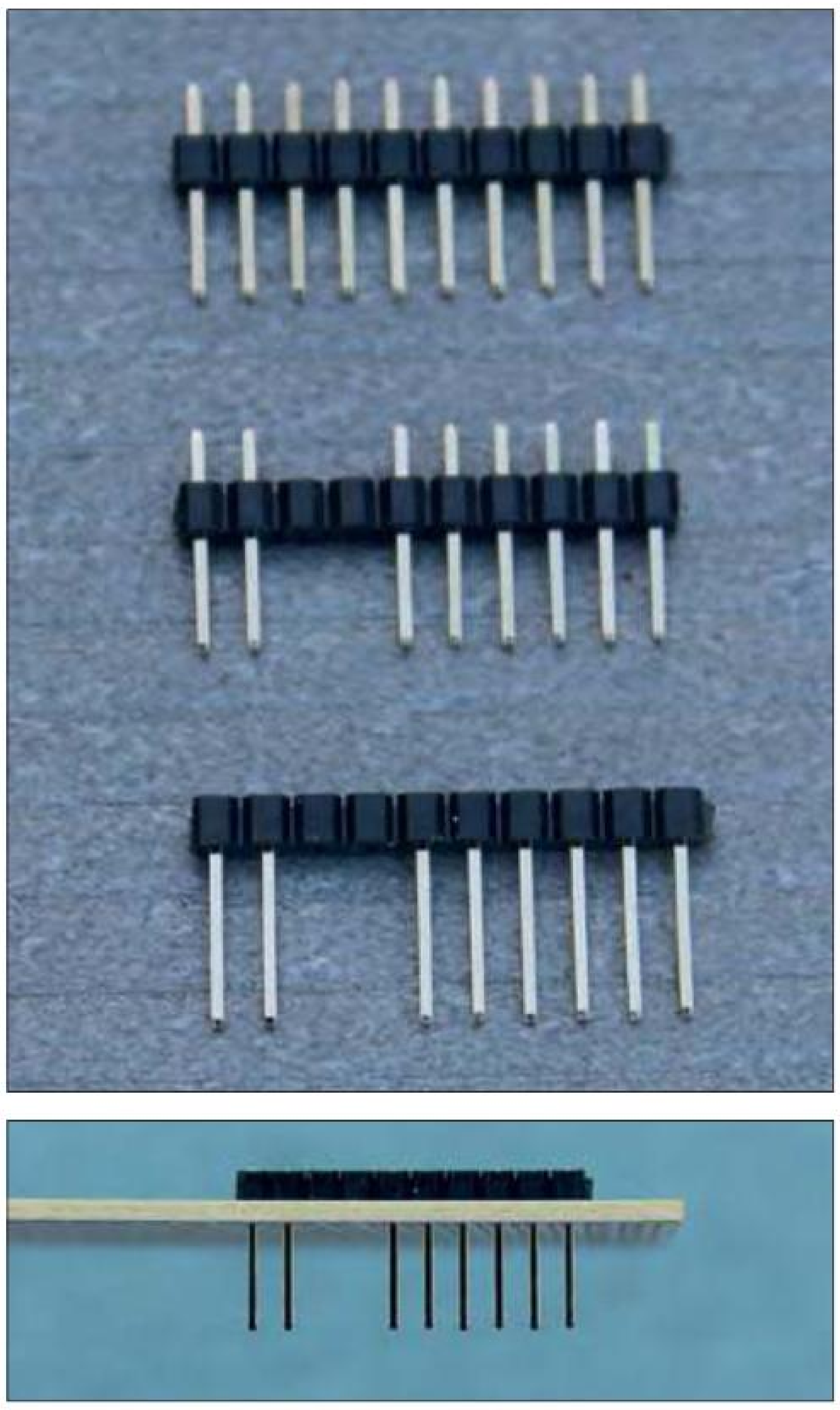


Fig.5. Pin strips J4 and J5 combined into a single modified pin strip.

Step 2: Install the wire links

There are many wire links to install – take your time and check each one as you go. Note the diagonal link G6-F9. This needs to be installed *before* the 14-pin DIL socket (which will sit on top of this wire-link). Start on the top row (A) and methodically work your way down to row i. Do not rush this part of the construction!

Step 3: Resistors

Next, install the two 10kΩ resistors (R4 and R5) into rows K and J. The remaining resistors are all 470Ω. Note that R8 stands vertically, with the body of the resistor over location C12 – see Fig.2 and Fig.3.

Step 4: Capacitors

There are just two 10µF tantalum capacitor to install. Remember that these are polarised, meaning they have to be inserted the correct way round. The longer positive leads are in D19 for one, and D20 for the other.

Step 5: Buttons

Insert the two tactile buttons into the required positions. Prior to soldering, check that the body of the button is flat against the stripboard.

Step 6: Semiconductors

Begin with the voltage regulator. Ensure that the flat part of its body is facing the two tantalum capacitors. Next, install the red LED, ensuring that the longer positive lead (anode) is in position D13. For the green LED, the longer lead is in position D23. Next up, install the 14-pin DIL socket, which will sit on top of the diagonal wire link. Prior to soldering, check it is definitely in the correct location; and then solder two diagonally opposite corner pins. Check the socket is level (it won't sit totally flat on the board because of the wire link underneath it). Once level, solder the remaining 12 socket pins. Install the MicroBridge IC into the socket, ensuring pin 1 is in the lower left corner – you may need to bend the pins slightly so it fits into the socket. Take care doing this, and do check that all pins are inserted correctly into the socket.

Step 7: Female sockets

If you purchased your *DM* kit from **micromite.org**, then you will need to cut down the supplied 15-way socket (J10) to convert it into a 14-way socket. Refer back to the details given for the *MKC* in *Part 2*.

J2 and J3 are both 6-way. Insert them into the required locations, soldering just the end pins initially. This will allow you to get them nice and straight before soldering the remaining pins. Repeat for the 14-way (J10), and the three 4-way sockets (J7, J8, and J9). (Note that the 2-way socket (J1) shown in Fig.2 is not required at this stage, and is not included in the kit. Do *not* fit anything in positions O3 and O4.)

Step 8: Pin strips

The four pin strips (shown in blue in Fig.2) need preparing prior to installation. Once prepared, they are inserted *upside down* through the *top* side of the board so that their long pins poke out on the *underside* of the board. These pins then allow the *DM* to be plugged into the *MKC*. Note also that pin strip J4 and J5 can be combined, as described shortly.

J6 is a 6-way pin strip, and J11 is a 14-way pin strip. For J4 and J5, simply use a single 10-way and remove the third and fourth pin (see Fig.5). Once you have these three lengths, take each one in turn and push each short end down, so its end is flush with the plastic. Use a hard, flat tool such as the blade of a flat screwdriver. Now drop J6 (6-way) into the board, hold it in place while turning the board over and solder the two end pins. Repeat for the combined 10-way for J4 and J5. Check these two are in line, and if necessary reheat and reposition. Once these two pin strips are perfectly in line, solder the remaining pins. Repeat for the 14-way pin strip (J11) – see Fig.4.

Testing

You could simply take the *DM* that you've just completed and plug it into your *MKC* in the hope that everything works properly; however, it is strongly recommended that you don't do that in case of any errors. Instead, let's take a step-by-step approach so that it's easier to pinpoint any issues.

Testing is best done with a multimeter (reading voltage), but if you don't have access to one, then a simple LED test circuit can be used instead (as described for the *MKC* testing).

First, power up the just *MKC* and check its Power LED comes on. If not – check your power source.

Remove power and have another visual check on the solder side of the *DM* board for any shorts. If everything appears to

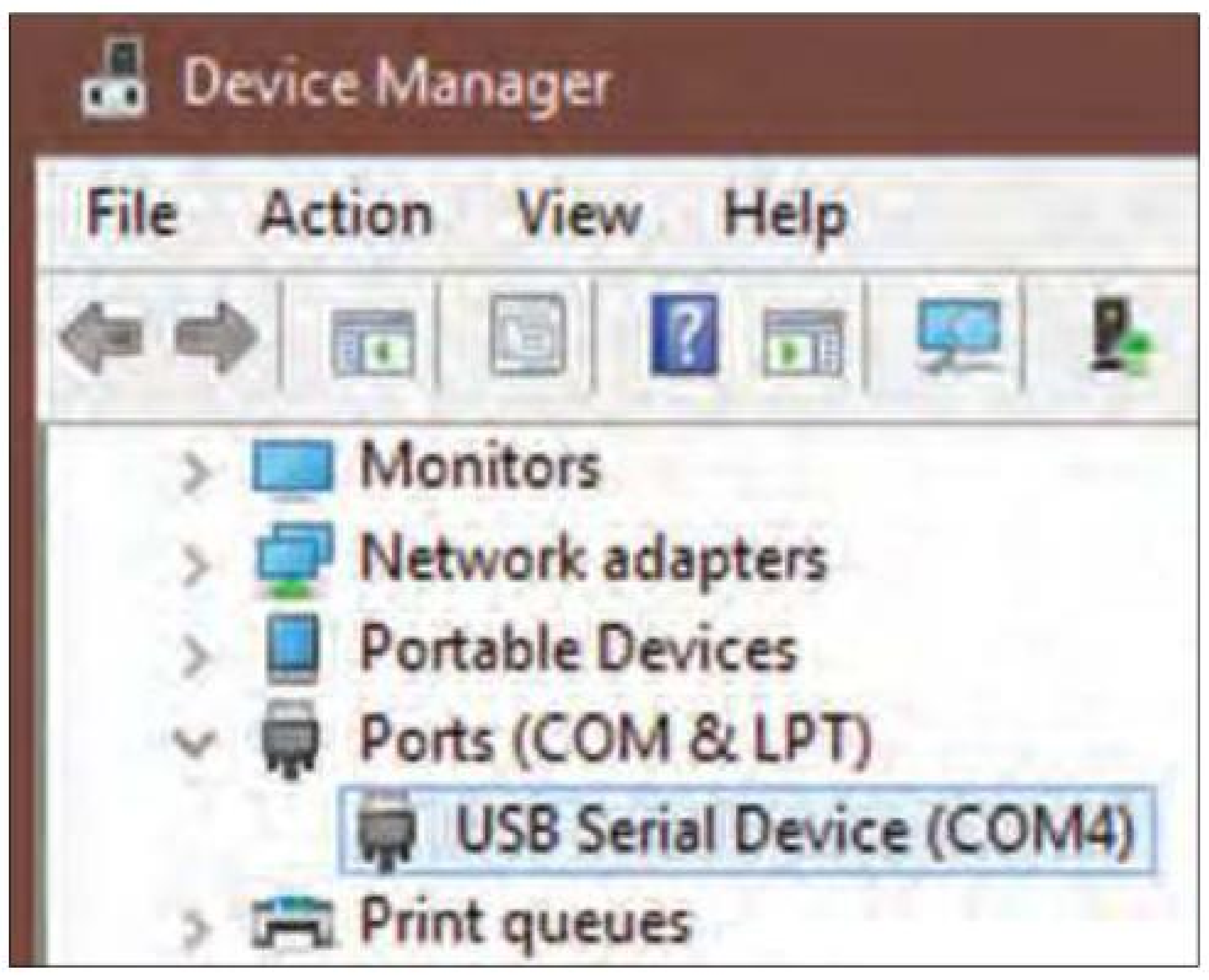
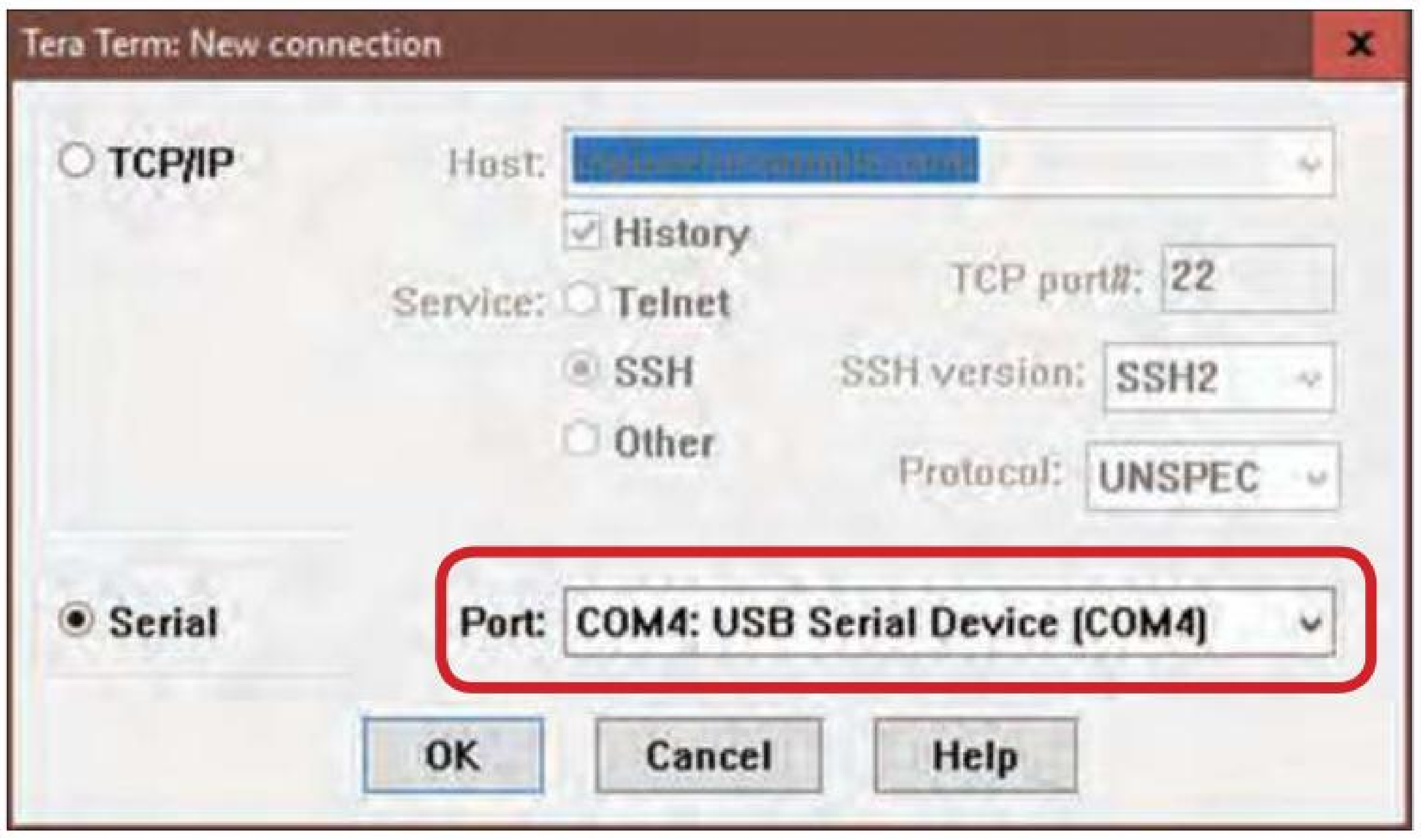
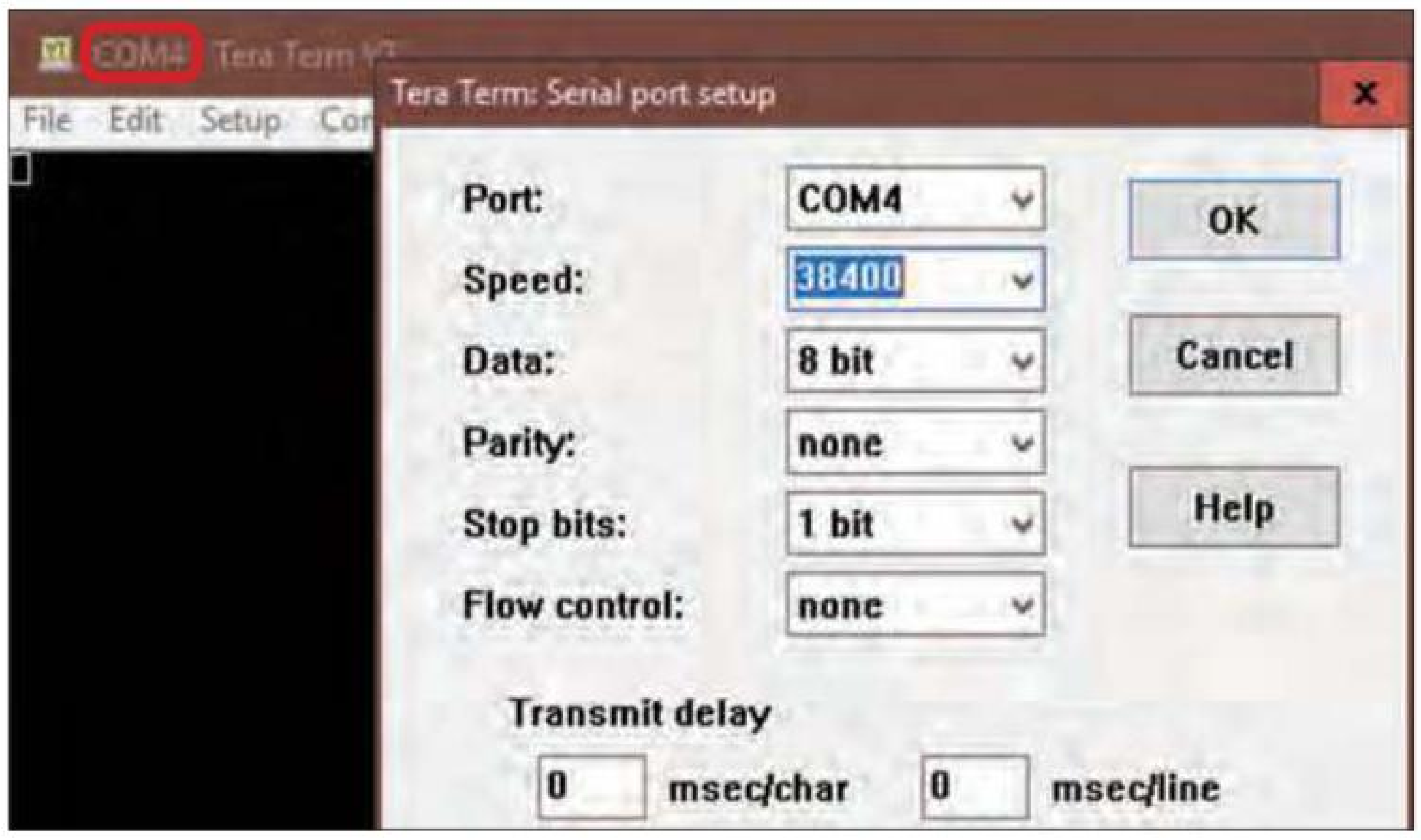


Fig.6. You can find which Virtual Com port has been assigned to the *DM* via your PC's Device Manager – COM4 in this example.



☑ History
TCP port#: 22
● SSH
SSH version: SSH2
Protocol: UNSPEC
● Serial
Port: COM4: USB Serial Device (COM4)

Fig.7. TeraTerm start-up screen – note highlighted Port selection.



Port: COM4
Speed: 38400
Data: 8 bit
Parity: none
Stop bits: 1 bit
Flow control: none
Transmit delay
0 msec/char 0 msec/line

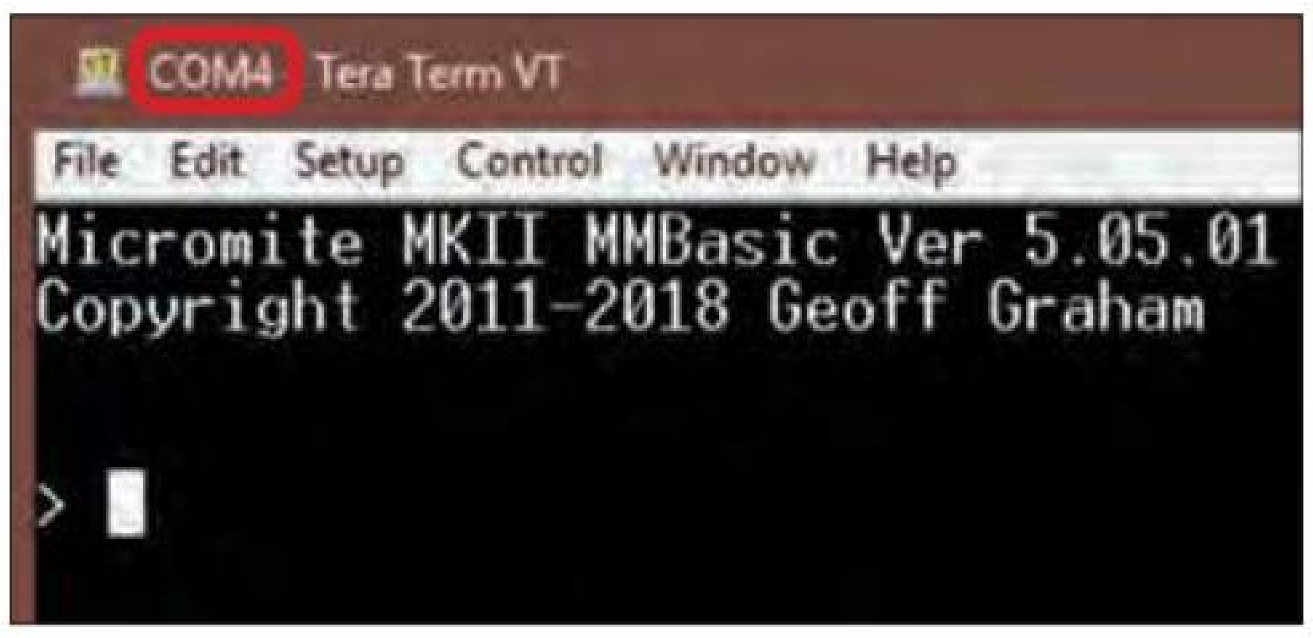
Fig.8. TeraTerm serial port set-up screen.

be fine, carefully plug the *DM* into the *unpowered MKC*, ensuring you line up all the pins correctly.

Now power up the *MKC* and check that the *MKC's* Power LED still lights up. If it doesn't, immediately remove power because something is wrong. Carefully unplug the *DM*, then power up the *MKC* once again to ensure it still powers up correctly. When unplugging the *DM*, do check that all the pins were lined up and inserted correctly. If they weren't, then this is the likely reason that the *MKC* did not power up with the *DM* incorrectly inserted. Reinsert it correctly, and try powering up again. If the *MKC* still fails to power up then it is time to power down and do a thorough check as something is wrong somewhere with the *DM* – check all aspects of construction: position, track cuts, shorts and polarised component orientation.

If you were successful with the *MKC* power up when the *DM* was plugged in, then check that the green Power LED (on the *DM*) lights up. If not, then take your multimeter (or test LED) and check the voltage between the 4-way sockets J7 (0V) and J9 (5V) – remember, the LED's shorter lead is the one that goes to 0V. If the test LED lights up, but the green Power LED doesn't, then you either have the Power LED the wrong way round, or a wire link in the wrong place. Next, if the test LED lights up (between sockets J7 and J9), check for a voltage between sockets J7 and J8 – it should be 3.3V. If the test LED fails then this implies an issue with the voltage regulator circuit – check for shorts, position and orientation.

Once you have both the *MKC* and *DM* Power LEDs lit, briefly press the Mode button (S2) and check that the red Mode LED lights up. If not, check that the MicroBridge IC is inserted correctly (Pin 1 bottom left, no pins missing their socket hole). Note that this test will only work if the MicroBridge software is installed on the *DM* PIC (IC1) – it will not work on a 'blank' PIC. *DM* kits purchased from **micromite.org** will have the MicroBridge software installed.



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Micromite MKII MMBasic Ver 5.05.01
Copyright 2011-2018 Geoff Graham

> 
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Fig.9. Success! – the Micromite welcome message in the TeraTerm window.

If the red LED (D1) did not light up when S2 was pressed, then check the voltage on Pin 8 (top right corner) of IC1. If there is approximately 3.3V present, then chances are the red LED is the wrong way around. You can use your test LED circuit if you do not have a multimeter – if it lights up when the test-probe touches pin 8, then D1 is the wrong way round.

If you were unsuccessful with the S2/D1 test, then the thing to do is carefully unplug the *DM* and then take a break! Come back when you feel fresh and perform a thorough check on the *DM*. First, examine all the wire link locations, then component positions. If all these check out, then turn the module over and check all the track cuts are located correctly.

If you are still stuck, then we are here to help you. Simply take two high-resolution photos; one of the component side (directly above), and the other of the soldered side. Make sure these are sharp, and that it is possible to zoom in on the detail. Then email them to: **contactus@micromite.org** (make the subject: 'HELP needed with MKC/DM').

We will do our best to help you out via email. However, if we cannot see anything obvious from the photos, then we offer a 'repair service' whereby you can send in your *MKC* and/or *DM* and we will get it going for you. (If you purchased any of the kits from us, then please quote your order number.)

Finally, do check our blog at **micromite.org** as there may be something posted there that will help resolve any issues.

Connecting MKC and DM to a computer

If you have a working *MKC* and *DM* (ie, the Mode LED lights when the Mode button is pressed), then it is time to prepare a computer and establish communication with the Micromite.

The majority of Micromite users we speak with are Windows Users so we will explain here the steps required when connecting to a Windows computer. If you are a MacOS user then we will explain what to do in a future issue and blog.

In simple terms, we have two things to prepare on a PC: a device driver (to allow the PC to communicate with the *DM*), and a Terminal program (to allow us to view and edit the code in the Micromite). This is a one-time setup, and is probably the only thing you'll find a bit confusing in this whole series, so follow along closely. The tricky part is configuring the PC.

Device driver

If you have Windows 10, then you can skip this section as the device driver is already installed. For all other versions of Windows, you will need to install the necessary device driver so that Windows can communicate with the MicroBridge (the PIC inside the *DM*). Visit **http://geoffg.net/microbridge.html** and scroll to the bottom of the page where you will see a 'Downloads' section. Click on the Windows download link to download the Windows Driver. Once downloaded, use the Driver Installation Tool, and follow the on-screen instructions.

With the device driver installed correctly, the MicroBridge will appear as a 'USB Serial Port' to your computer when it is plugged in. Go ahead and connect your *MKC* to your computer (with the *DM* plugged in). The first thing to check is that both Power LEDs are lit. Also ensure that the red Mode LED (D1) is OFF. If the Mode LED is on, then press the Mode Button (S2) for three seconds, by which time it will flash, and then go out. Windows should automatically assign the MicroBridge with a Virtual COM port number. You can find out what this number is by checking Device Manager -> Ports (COM & LPT) – see Fig.6. It will show as a USB Serial Device (COMx). Make a note of the number 'x' – we will need this in the next step.

Terminal program

In *Part 1* we recommended downloading the *Getting Started With the Micromite guide*; and also the *Micromite User Manual*. Go back to them and read the section about configuring TeraTerm; the Windows Terminal program that we will be using to communicate with the Micromite. At the time of writing, the current *Micromite User Manual* is version 5.05; and the TeraTerm (Terminal Emulator) section starts half way down page 9. Refer to this for the following step.

If you have not already done so, download TeraTerm from: **https://tera-term.en.lo4d.com/**

When you run TeraTerm, select the Serial radio button (as opposed to TCP/IP) – see Fig.7. Then use the drop-down to select the COM Port number from the previous step – it should automatically be there in the list. Hit the 'OK' button and TeraTerm should then connect to the MicroBridge via the Virtual COM port assigned by Windows.

The last thing we need to do is set the correct speed (baud rate) for the connection. Go to the Setup > Serial Port option to show the screen, as illustrated in Fig.8. Ensure the Baud rate is set to 38400. Check the other settings match the screen shot (they will likely be the same if it is the first time you are running TeraTerm). Hit 'OK' to save these settings.

If everything is set up correctly, then anything typed on your computer's keyboard will be sent via the serial interface of the MicroBridge, and anything received on this interface will be sent to the TeraTerm screen window. To aid in fault finding, the red Mode LED on the *DM* will flash for every character sent or received.

Now for the moment of truth – press the Reset button (S1) on the *DM* and a welcome message should appear in the TeraTerm window (see Fig.9). If so, then Congratulations; you have successfully built and set up your *MKC*.

If you purchased the *MKC* kit then there will be a test program pre-installed. This program automatically runs when power is applied to the *MKC*. As a final test of the kit, hold down the 'Ctrl' key and press 'C'. This will stop the program running and you will see a cursor appear in the TeraTerm window. If you type LIST and hit the Enter key, then you will see the program code.

Recommended reading

We have covered a lot of construction over the last two months and hopefully everything is working for you. If things are not quite working yet, then don't despair – get in touch with us and we will help you out.

If everything has tested out OK, then why not have a play with your new Micromite Computer. Have a read of Chapter 2, and Chapter 3, from *Getting Started With the Micromite* and try some of the many examples described.

To stop the 'test-program' which is on your Micromite (and automatically runs on power-up), first press Ctrl-C (as mentioned above), and then type NEW at the cursor (and hit enter). This will clear the program from memory. Now, if you press the Reset button (S1), you should see the Micromite 'Welcome' message, along with a cursor which indicates the Micromite is waiting for you to type something. You can then work through Chapters 2 and 3.

Preparations for next month

Next month, in *Part 4*, we will start to explore MMBASIC. We will learn about how to use digital inputs and outputs, and show you just how easy it is to control things with MMBASIC. We will build some simple circuits on a breadboard, and connect these to the *MKC* with jumper wires.

Do make sure you have a breadboard and some jumper wires. Or, for a chance to get these items for *free,* enter the competition below. Also grab some 3mm or 5mm LEDs and some current-limiting resistors (any value from 470Ω to 1kΩ).

Questions? Please email Phil at:
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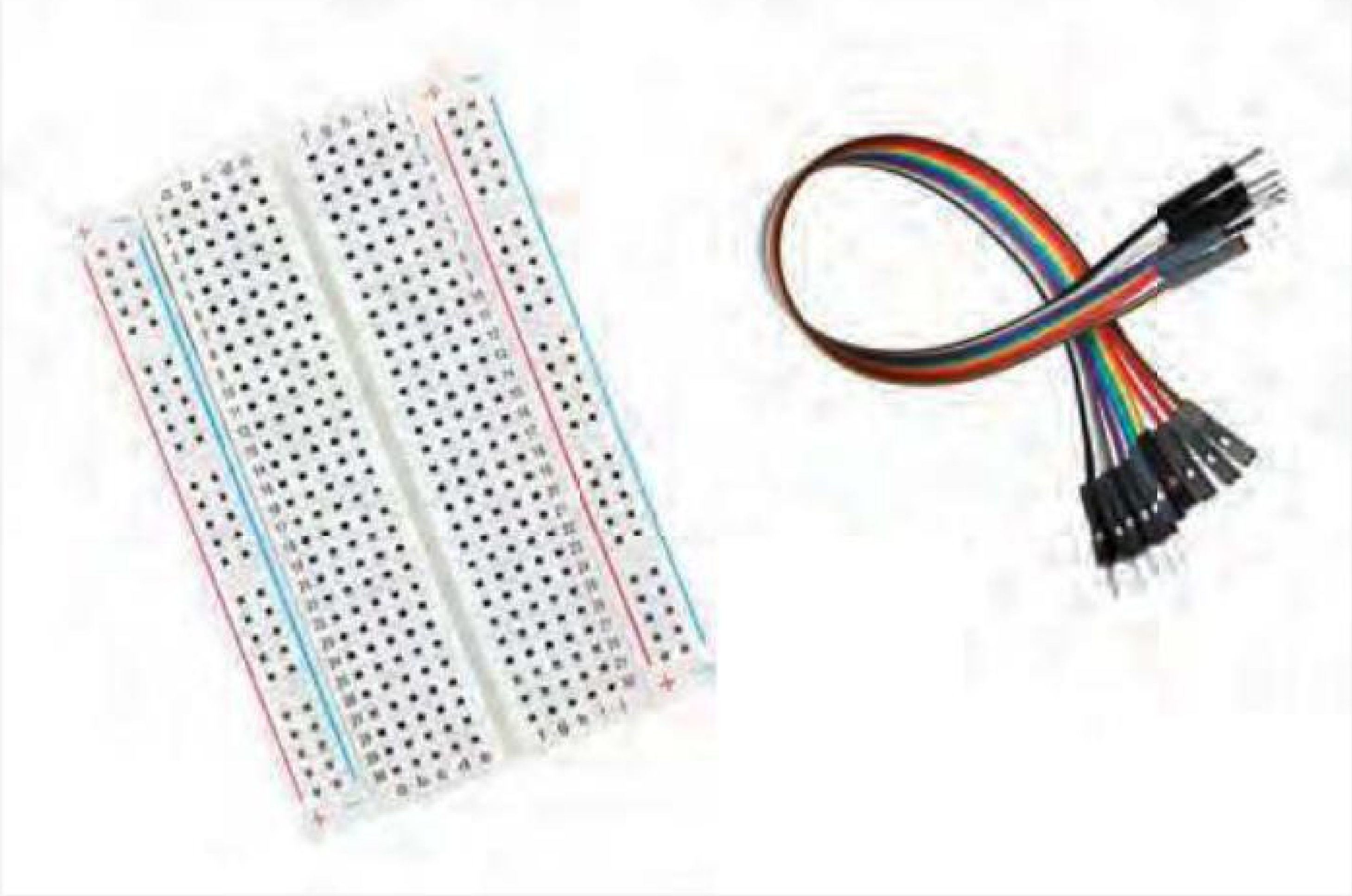

Competition!

Something slightly different this month. For those of you following the *Make it with Micromite* series, we would really like to see a photo of your *Micromite Keyring Computer* (*MKC*) and *Development Module* (*DM*) working.

The first 10 people to send us photo(s) of their *MKC* connected to TeraTerm will recieve a breadboad and a set of jumper wires.

To enter the competition, email your photo(s) to **epe@micromite.org** with email subject 'MIWM3'.

Please ensure you email before the competition closing date: 31 March 2019

We really want to encourage you to follow and enjoy this series. If you run into any issues, or just need some help, then drop us an email at: **contactus@micromite.org**

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1. Maximum of one 'Breadboard and Jumper set' per person
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3. Winners will be notified by email within one week of the closing date
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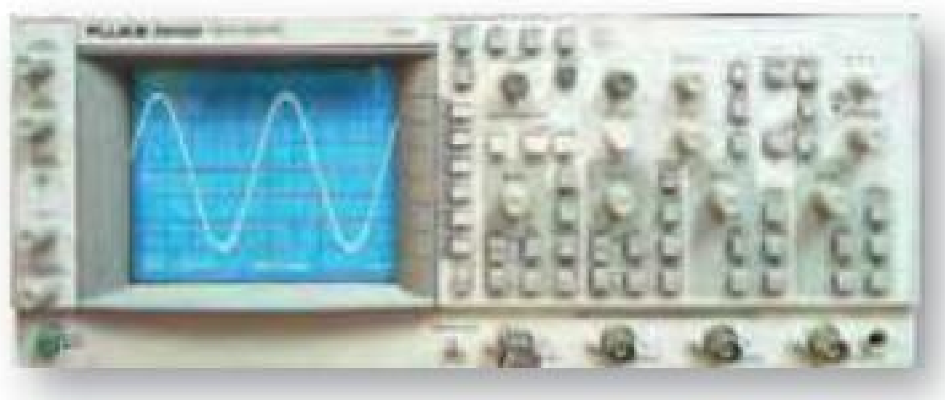

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Max's Hot Beans

By Max the Magnificent

Most non-engineers and many junior engineers are under the impression that when they flip a toggle switch or press a push button, it transitions between the OFF and ON states in a smooth and seamless way. Take a light switch on the wall, for example. When we activate the switch, the light appears to turn on cleanly. It's as simple as that... or is it? In reality, the switch can bounce on and off like a ping-pong ball being dropped on a wooden table. The only reason we don't notice this is that it happens too quickly for the human eye to detect. Things are different when we are talking about microcontrollers (MCUs) with system clocks running at millions, tens of millions, or hundreds of millions of cycles per second. If we don't do something to mitigate the switch-bounce effect, our microcontroller might see a single flick of a switch as representing a large number of transitions.

Switch bouncing around

For the purpose of these discussions, let's consider an SPST (single-pole, single-throw) switch, where the number of poles refers to the number of separate circuits the switch can control, and the number of throws refers to the number of contacts (wiring paths other than 'open') to which each pole can connect. Furthermore, let's consider this in a typical configuration, with its 'main' (pole) terminal connected to GND and its 'secondary' (throw) terminal connected to the positive V_{DD} supply via a pull-up resistor (Fig.1).

When the switch is in its inactive/off position, the NO ('normally open') terminal is pulled up to a logic 1 value. When we close the switch (we use the term 'make' as in 'make the connection'), the 'spring-loaded' mechanical contact may bounce back and forth between 0 and 1 values a number of times before finally settling into a 0 state. Similarly, when we subsequently reopen the switch (we use the term 'break' as in 'break the connection'), the contact can once again bounce back and forth between 1 and 0 values before eventually settling on a 1.

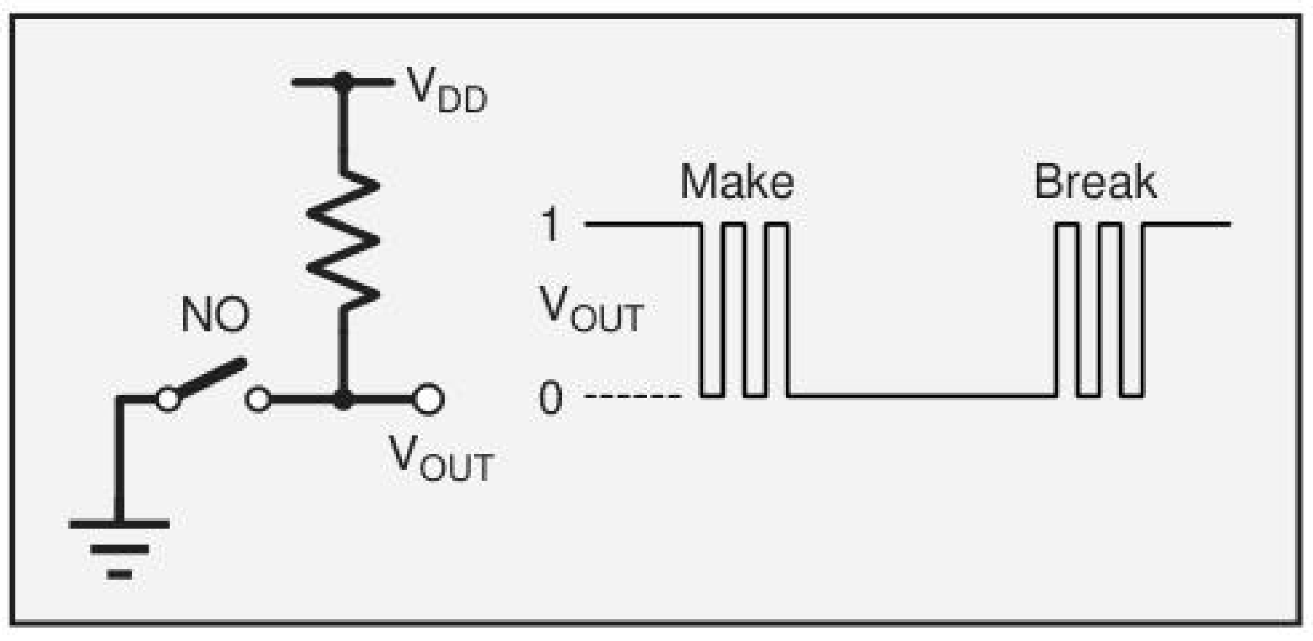

Fig.1. SPST (single pole, single throw) switch.

Have you ever pressed a button on something like a TV controller and been annoyed when the system jumped over a number of channels? What caused this? The answer is almost certainly switch bounce or – more accurately – the fact that the designer of this device didn't take appropriate precautions to mitigate against switch bounce effects. The bottom line is that, if you are in the business of creating electronic projects or products, you are going to have to deal with switch bounce by one means or another.

Debouncing an SPST switch

If you search the Internet, you will discover myriad suggestions for debouncing your switches. Unfortunately, many of these are based on anecdotal evidence ('I heard from a friend of a friend that he heard from an old engineer the tale of a switch that ...'). For example, I've often heard that no switch bounces for more than 1ms (one thousandth of a second), so if we double this to 2ms we should be safe, right? Hold your horses...

One authoritative source is embedded engineering legend Jack Ganssle, who performed (and documented) a suite of tests on a collection of switches (**https://bit.ly/2D9KueF**). Jack reported that the average switch bounce duration was 1.6ms, with a maximum of 6.2ms. (He also found one switch that bounced for a whopping 157ms, although he considered this switch to be a faulty outlier.) Meanwhile, one of my chums who was a technician in the US air force tells me that they specified 20ms, just to make sure.

When it comes to debouncing our SPST, we can opt for hardware or software solutions. You might question why we don't always do things in software, but it may be that our MCU has enough to do and we want to offload as many tasks as possible. A simple SPST debouncer circuit is shown in Fig.2.

The idea here is that charging and discharging the RC (resistor-capacitor) combo smooths (filters) out any bounces from the switch opening and closing. (Choosing the appropriate values for the resistors and capacitors is an exercise in its own right, but we don't need to go into that here because – in a little while – I'm going to make you very, very happy.) The buffer gate is used to 'sharpen' the edge on V_{OUT}. Furthermore, as we see from the symbol, this is a Schmitt buffer with hysteresis, which will stop any small ripples on the input from being seen as switching events.

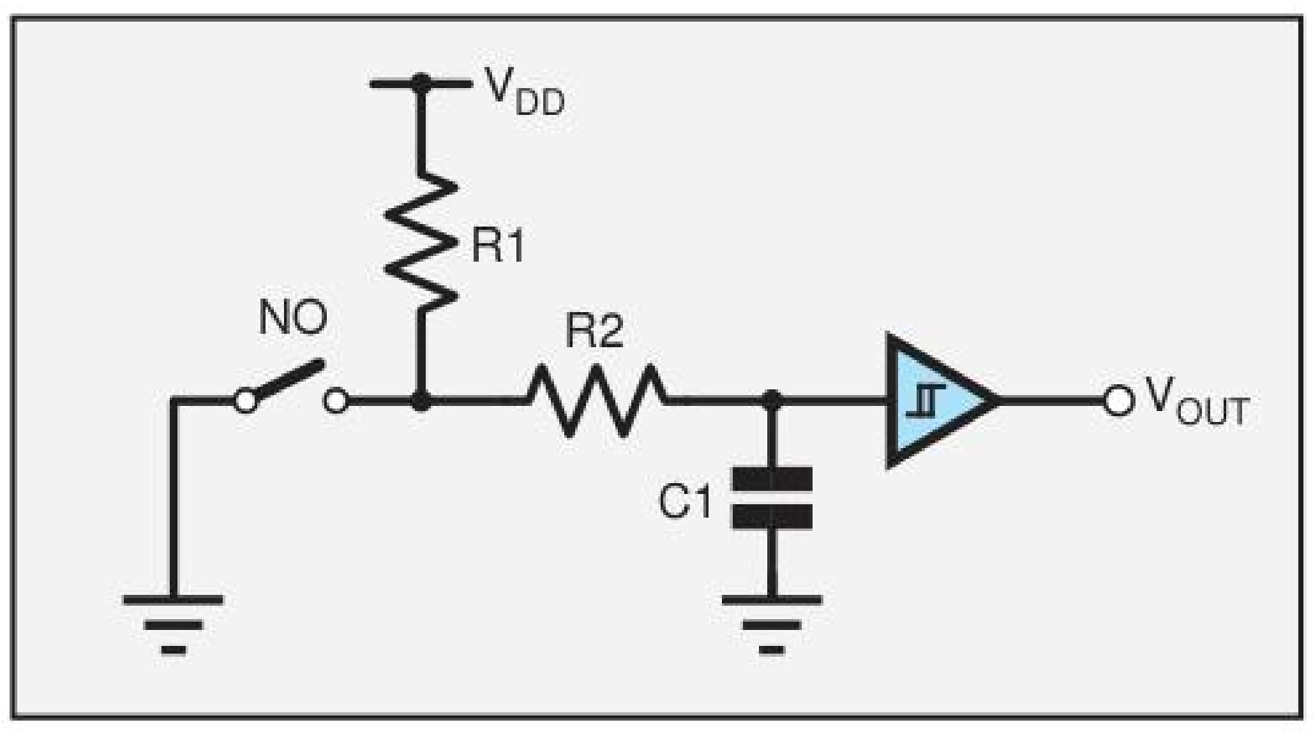

Fig.2. Simple SPST debouncer circuit.

If we decide to debounce our switch in software, then one approach is to use a counter to time how long the switch has been in its new state. Let's assume that the V_{OUT} signal in Fig.1 is connected to one of the inputs on our MCU. Let's also assume that we start off with our switch in its open state, which means $V_{OUT} = 1$. In this case, we could wait until we see V_{OUT} go to 0, indicating the switch has been closed, at which point we could reset our counter to 0 and start sampling this signal periodically (every millisecond, for example). Every time we sample, we increment the counter if V_{OUT} is still 0, or we reset the counter to 0 if V_{OUT} is 1. It's only when the counter says the signal has remained 0 for a specified amount of time – say 20ms – that we consider the switch to be truly closed, at which point we could initiate whatever task(s) we wish to perform. We could perform a similar sequence of actions to determine when the switch has been well and truly opened again.

One problem with both of the techniques – hardware and software – presented above is that they add an element of delay into the proceedings. This delay is probably not significant if the switch is activated by hand, but it may be more of a problem in the case of an automatically triggered limit switch on a piece of industrial equipment. With regard to the software approach, there is a way around this delay, but – once again – we don't need to go there, because I'm about to make you very, very happy.

Introducing LogiSwitch ICs

One of my friends, Mike Pelkey, is credited with being one of the grandfathers of base jumping (parachuting or wing-

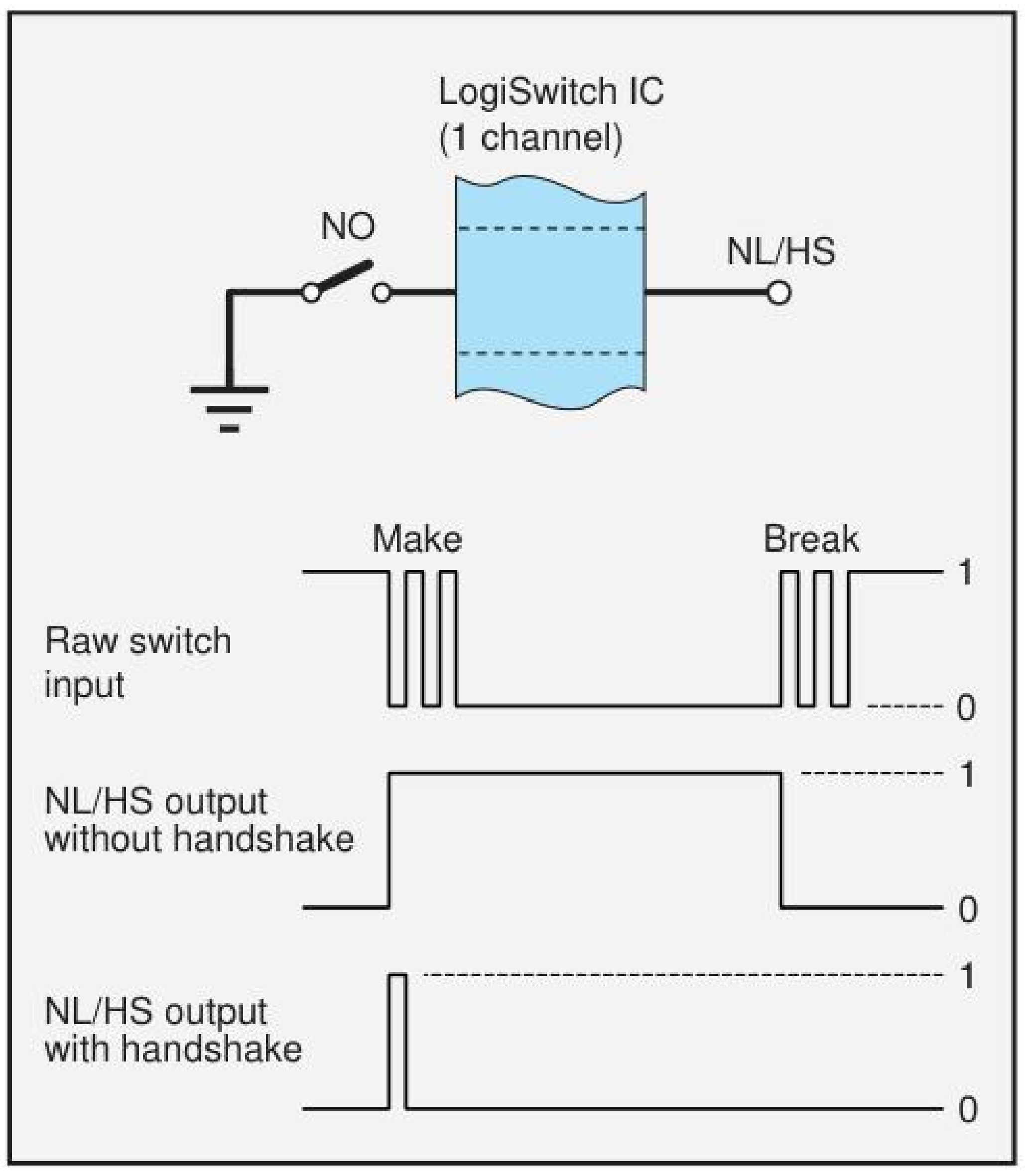

Fig.3. Single channel of a LogiSwitch IC.

suit flying from a fixed structure like a building, bridge, antenna, or cliff). Mike is also an engineer of renown; whose experience goes all the way back to the dawn of the microprocessor.

Like almost every engineer I know, Mike wrestled with switch bounce throughout his career, which encompassed more than 40 years of designing digital systems. Having employed almost every version of traditional hardware and software switch bounce mitigation techniques, Mike decided there had to be a better way. The result of Mike's cogitations and ruminations was the LogiSwitch concept (**https://bit.ly/2GnufxA**). Boasting adaptive bounce detection algorithms and a unique 1-wire handshaking protocol, LogiSwitch ICs reflect the state-of-the-art in switch bounce mitigation technology.

Low-cost LogiSwitch ICs (they start at $3.40; volume pricing is available) are presented in 3-, 6-, and 9-channel variants, where each channel can accommodate a single SPST switch. All variants are available in both surface-mount technology (SMT) and lead through-hole (LTH) packages, the latter making them perfect for hobbyists. The best way to illustrate how these devices work is to consider a single channel, as illustrated in Fig.3.

The LogiSwitch IC is powered via a pair of V_{DD} and GND pins. Each channel on the LogiSwitch IC has a single input pin (equipped with an internal pull-up resistor), which is connected to the raw switch input signal, and a single NL/HS (normally low with handshake capability) output, which is connected to the MCU.

First consider the NL/HS signal without the handshake protocol being employed. In this case, the MCU pin to which it is connected always acts like an input. The main thing to note here is that the NL/HS signal responds almost instantaneously to the initial make or break transition on the incoming signal, so the MCU sees the switch event as soon as it occurs without any artificial delays.

Now let's consider an example scenario in which we have a program loop that waits for the switch to be activated and then performs some action like incrementing a counter; something like: `if (pinNLHS == 1) counter++;` The problem is that the switch could be active for quite some time, so – if we aren't careful – we will end up incrementing our counter multiple times.

There are two ways in which we typically handle something like this. The first is to keep track of the switch's state ('open' or 'closed'), and to only increment the counter when the switch is first closed. The second is to wait for the switch to be closed, then increment the counter, and then wait for the switch to be opened again before restarting the sequence.

LogiSwitch ICs offer another possibility. As soon as the MCU sees that the NL/HS input has transitioned to 1, in addition to performing any tasks like incrementing the counter, we can change the mode of the pin to OUTPUT, pull the NL/HS signal to 0 for 50µS (that's 50 microseconds), then return the mode of the pin to INPUT.

When the LogiSwitch IC sees that the MCU is pulling its NL/HS signal low (this pin is driven by an open-collector output with internal pull-up), it will itself start to drive it to 0. This means that the next time the MCU reads this pin, it will see a 0. In turn, this means that the MCU no longer has to keep track of the switch's state.

I have to say that when I first saw this, I thought, 'Wow! That's clever! Why did I not think of this myself?' Suffice it to say that I'm now using LogiSwitch ICs in all of my projects (for example, I have a 3-channel device in my *Audio-Reactive Artifact* and three 6-channel devices in my *Inamorata Prognostication Engine*).

There's so much more to say about the switch bounce topic, but no time to say it here. Maybe in a future column…

Somewhere over the rainbow

I've been receiving a lot of interest from last month's column regarding my *Audio-Reactive Artifact* project, so I thought I'd provide a brief update. Once I'd finished wiring the LEDs and making sure they all lit up as planned, I decided to run a quick rainbow test pattern to see how the defunct vacuum tubes looked when illuminated from below with different colours. The way I did this was to divide the tubes into thirteen vertical groups (columns) in software, and then cycle a rainbow of colours across these groups. I must admit that I was a little worried that the structures in the tubes would block too much of the light, so I was very pleasantly surprised with the result (Fig.4.)

You can see a short video of this on YouTube (**https://bit.ly/2RAmC9g**), but I have to apologise for the quality; this was the best I could obtain with an iPhone and it really doesn't do the artifact justice. You can also peruse and ponder my Arduino code for this effect if you wish (**https://bit.ly/2BkmKEe**).

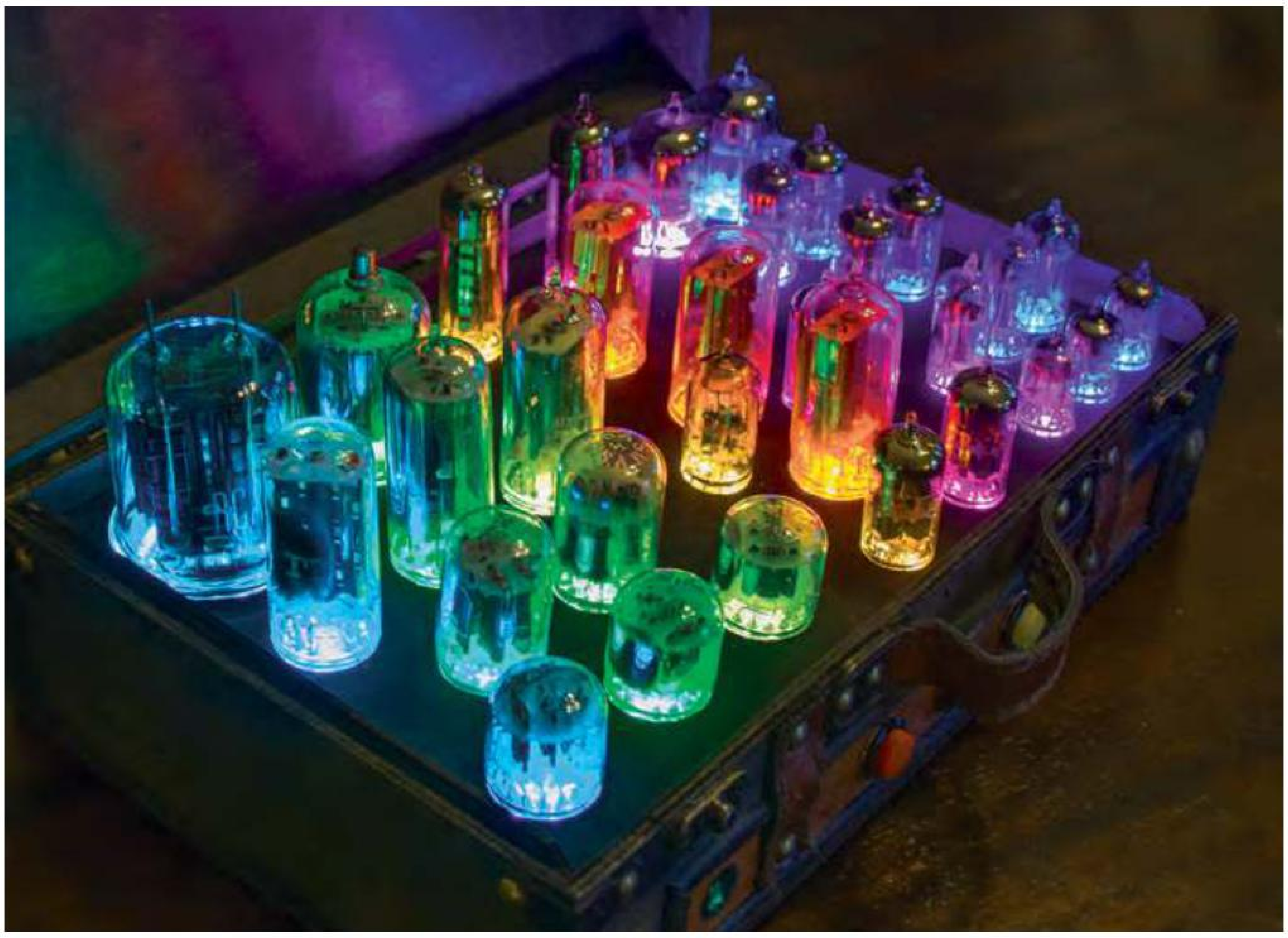

Fig.4. A rainbow of colours.

Hot bean Max Maxfield (Hawaiian shirt, on the right) is editor-in-chief at **EEWeb.com** – the go-to site for users of electronic design tools and askers of electronic questions.

Comments or questions? Email Max at: **max@CliveMaxfield.com**

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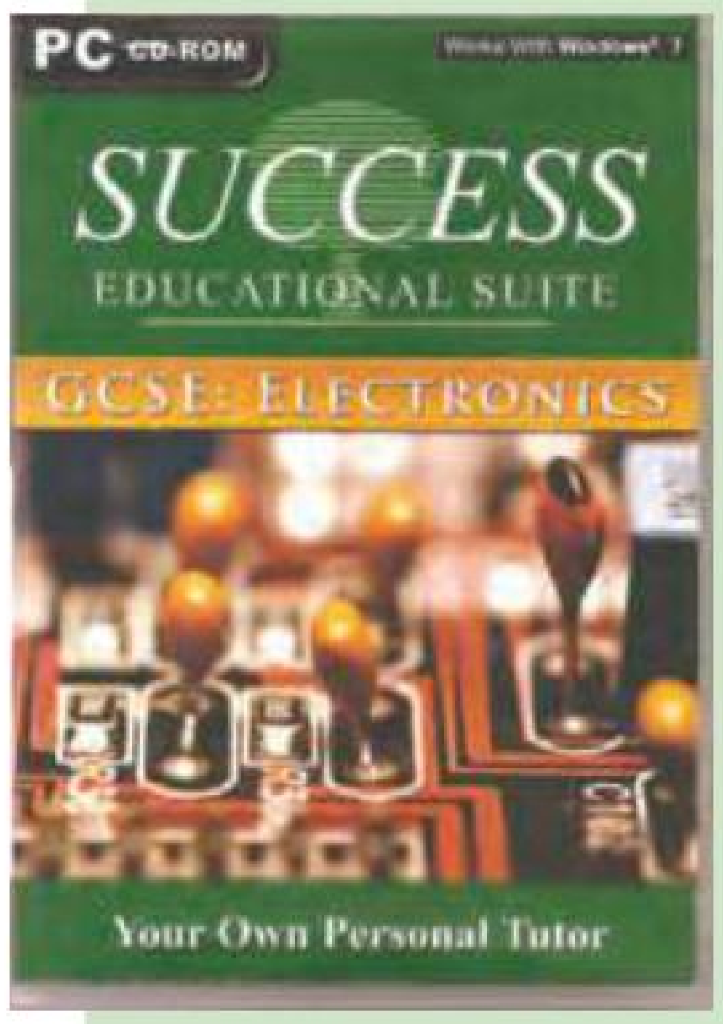

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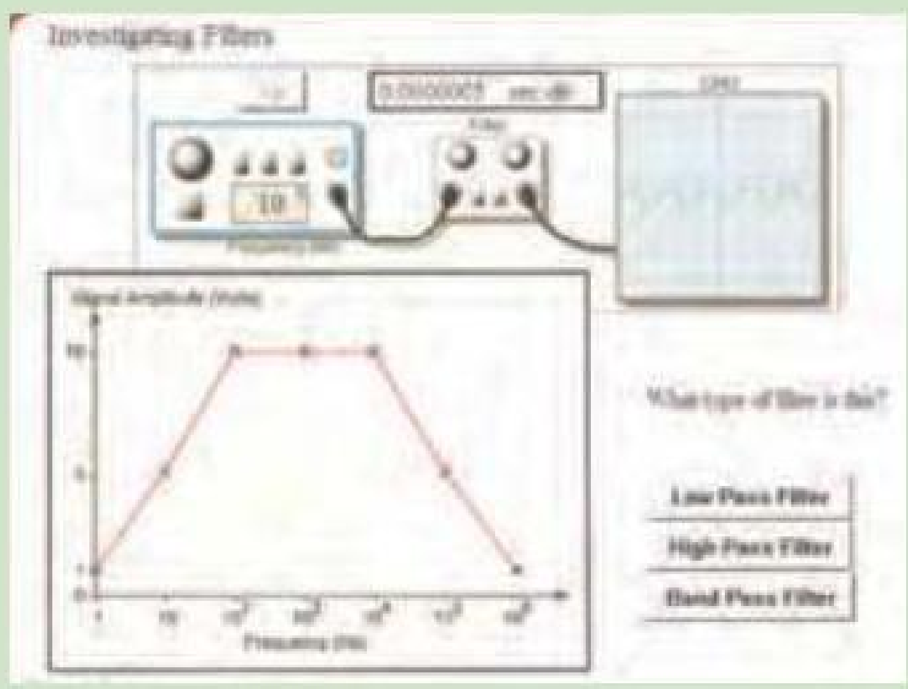

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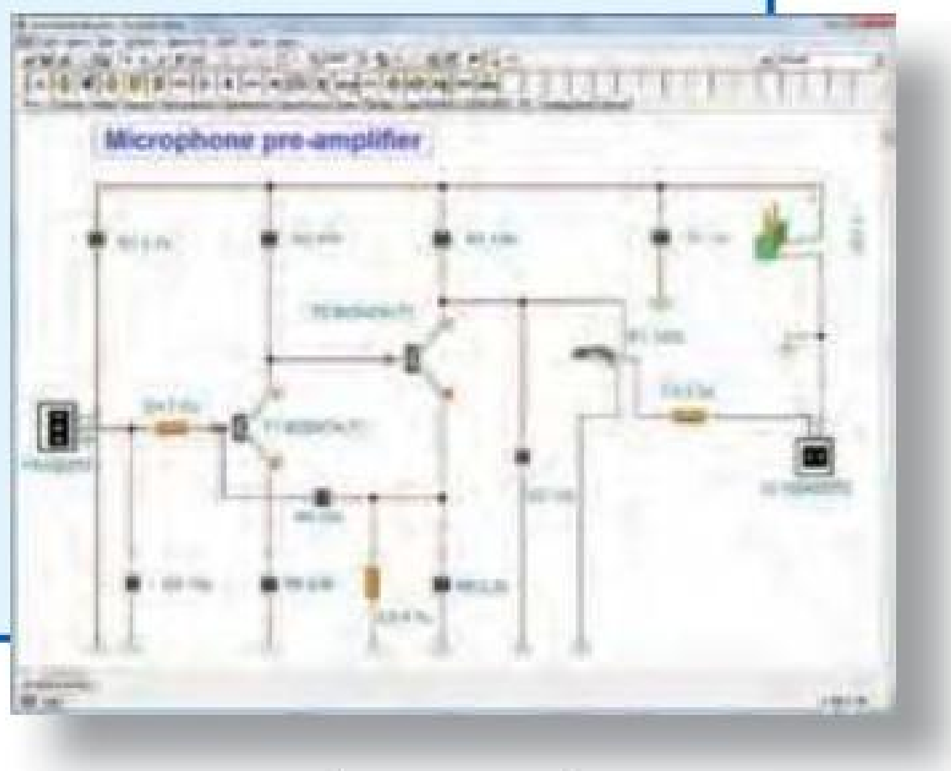

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SOFTWARE

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(Formerly PICtutor)

Assembly for PICmicro microcontrollers V3.0 (previously known as PICtutor) by John Becker contains a complete course in programming the PIC16F84, 16F88 and 16F877a PICmicro microcontroller from Arizona Microchip. It starts with fundamental concepts and extends up to complex programs including watchdog timers, interrupts and sleep modes.

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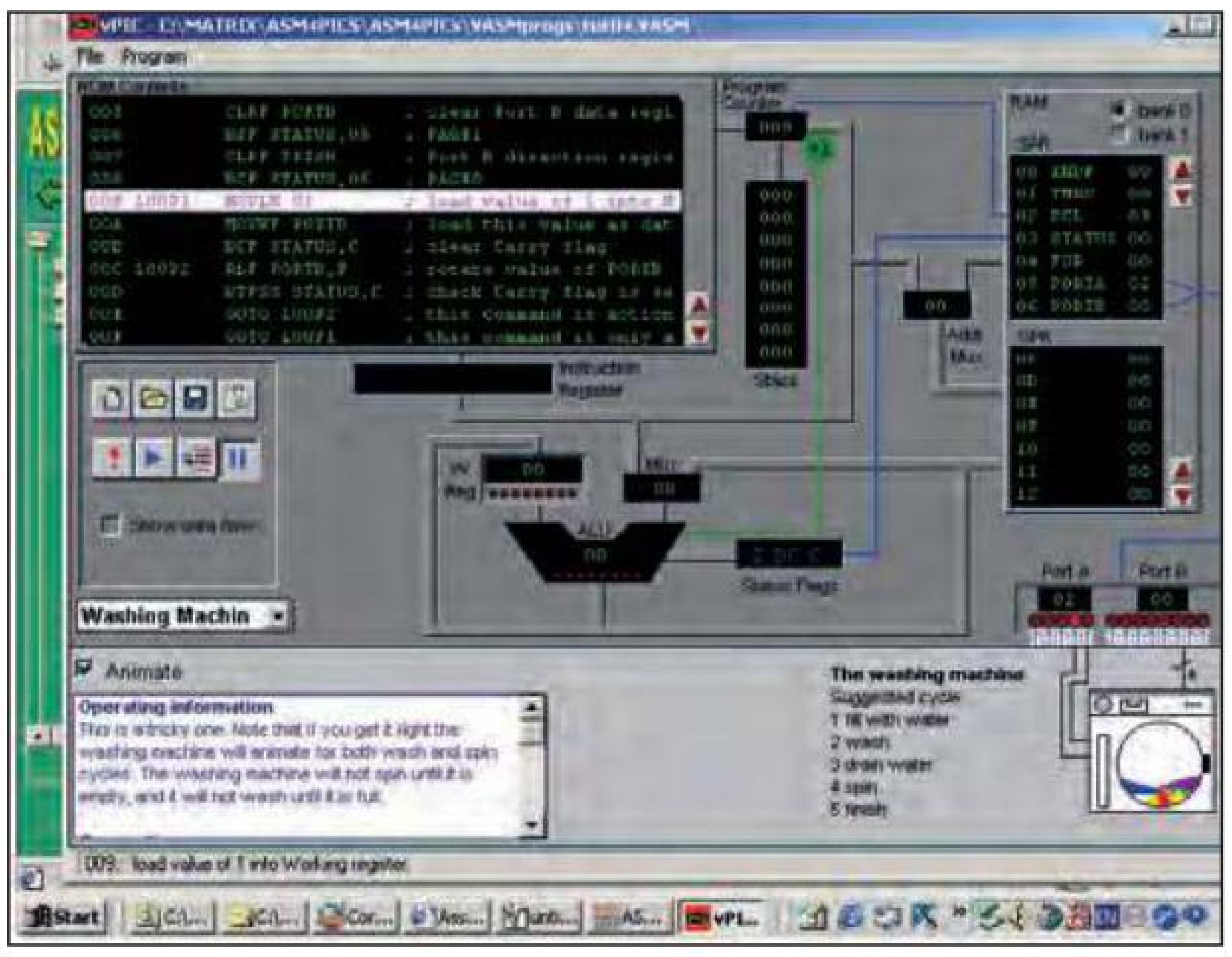

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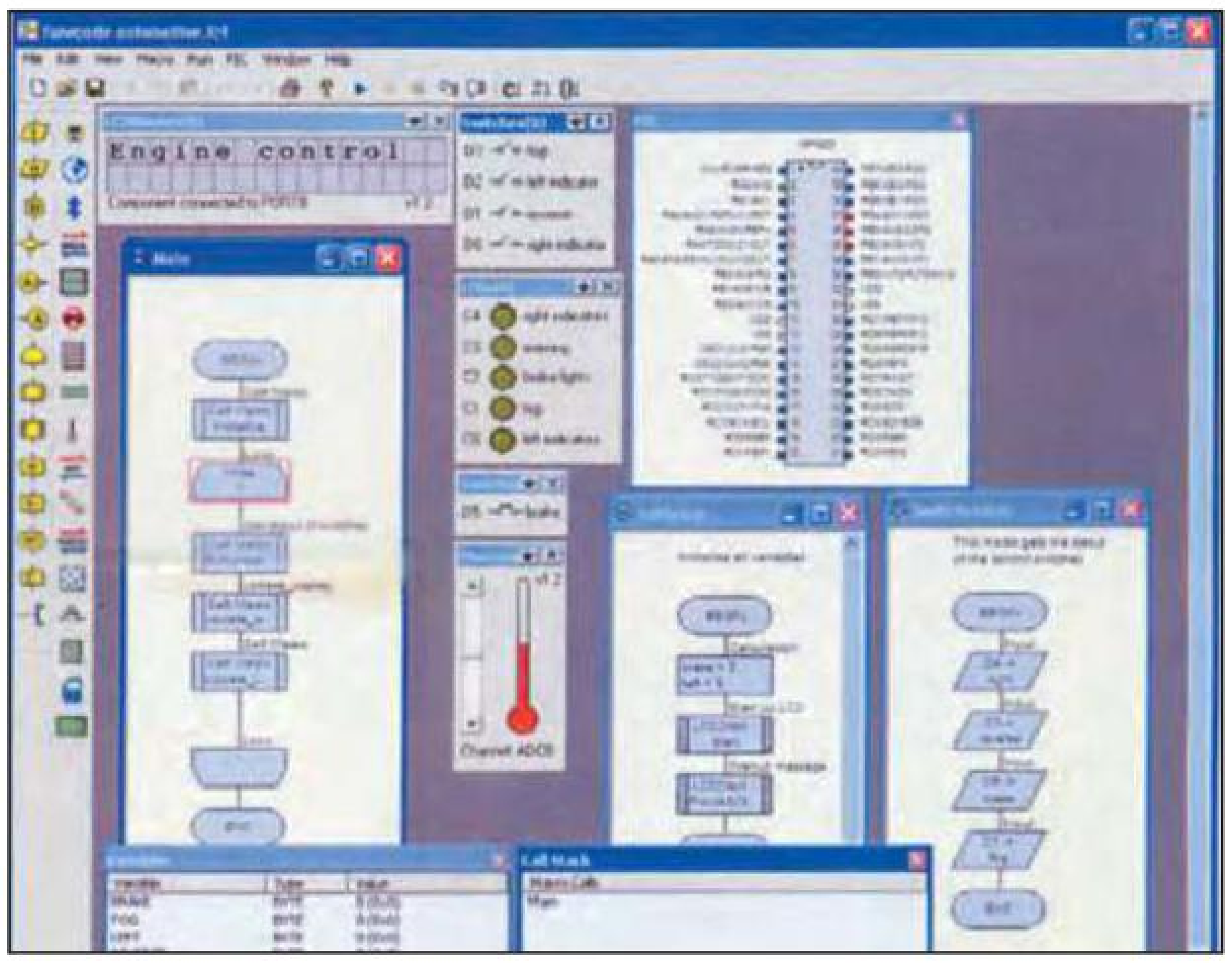

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ELECTRONICS TEACH-IN 2 CD-ROM
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This *Teach-In* series of articles was originally published in *EPE* in 2008 and, following demand from readers, has been collected together in the *Electronics Teach-In 2* CD-ROM.

The series is aimed at those using PIC microcontrollers for the first time. Each part of the series includes breadboard layouts to aid understanding and a simple programmer project is provided.

Also included are 29 *PIC N' Mix* articles, also republished from *EPE*. These provide a host of practical programming and interfacing information, mainly for those that have already got to grips with using PIC microcontrollers. An extra four part beginners guide to using the C programing language for PIC microcontrollers is also included.

The CD-ROM also contains all of the software for the *Teach-In 2* series and *PIC N' Mix* articles, plus a range of items from Microchip – the manufacturers of the PIC microcontrollers. The material has been compiled by Wimborne Publishing Ltd. with the assistance of Microchip Technology Inc.

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Teach-In 2017

Introducing the BBC micro:bit

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Python Coding on the BBC micro:bit
Jim Gatenby

PYTHON CODING ON THE BBC MICRO:BIT

Jim Gatenby

Python is the leading programming language, easy to learn and widely used by professional programmers. This book uses MicroPython, a version of Python adapted for the BBC Micro:bit.

Among the many topics covered are: main features of the BBC micro:bit including a simulation in a web browser screen; various levels of programming languages; Mu Editor for writing, saving and retrieving programs, with sample programs and practice exercises; REPL, an interactive program for quickly testing lines of code; scrolling messages, creating and animating images on the micro:bit's LEDs; playing and creating music, sounds and synthesized speech; using the on-board accelerometer to detect movement of the micro:bit on three axes; glossary of computing terms.

This book is written using plain English, avoids technical jargon wherever possible and covers many of the coding instructions and methods which are common to most programming languages. It should be helpful to beginners of any age, whether planning a career in computing or writing code as an enjoyable hobby.

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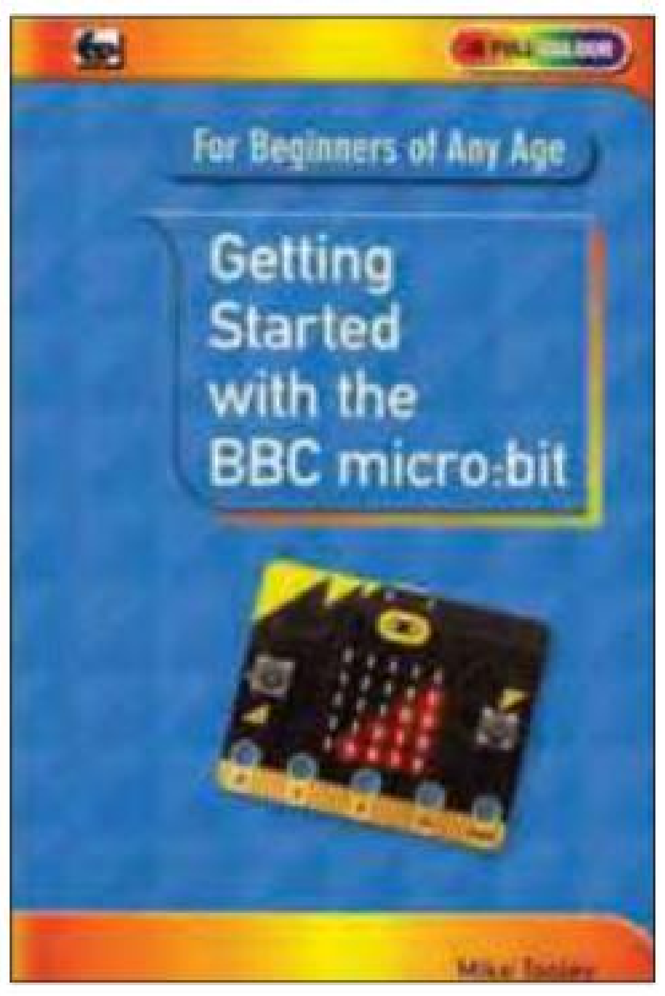

GETTING STARTED WITH THE BBC MICRO:BIT

Mike Tooley

Not just an educational resource for teaching youngsters coding, the BBC micro:bit is a tiny low cost, low-profile ARM-based single-board computer. The board measures 43mm × 52mm but despite its diminutive footprint it has all the features of a fully fledged microcontroller together with a simple LED matrix display, two buttons, an accelerometer and a magnetometer.

Mike Tooley's book will show you how the micro:bit can be used in a wide range of applications from simple domestic gadgets to more complex control systems such as those used for lighting, central heating and security applications. Using Microsoft Code Blocks, the book provides a progressive introduction to coding as well as interfacing with sensors and transducers.

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No previous coding experience is assumed, making this book ideal for complete beginners as well as those with some previous knowledge. Self-test questions are provided at the end of each chapter, together with answers at the end of the book. So whatever your starting point, this book will take you further along the road to developing and coding your own real-world applications.

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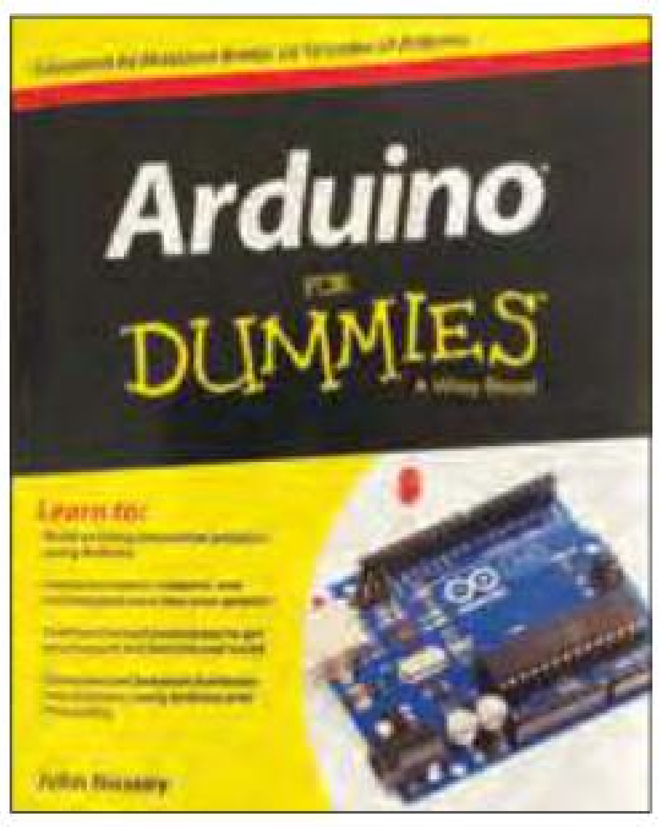
ARDUINO

Teach-In 2016

See opposite for our popular introduction to the Arduino



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John Nussey

Arduino is no ordinary circuit board. Whether you're an artist, a designer, a programmer, or a hobbyist, Arduino lets you learn about and play with electronics. You'll discover how to build a variety of circuits that can sense or control real-world objects, prototype your own product, and even create interactive artwork. This handy guide is exactly what you need to build your own Arduino project – what you make is up to you!

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Jeremy Blum

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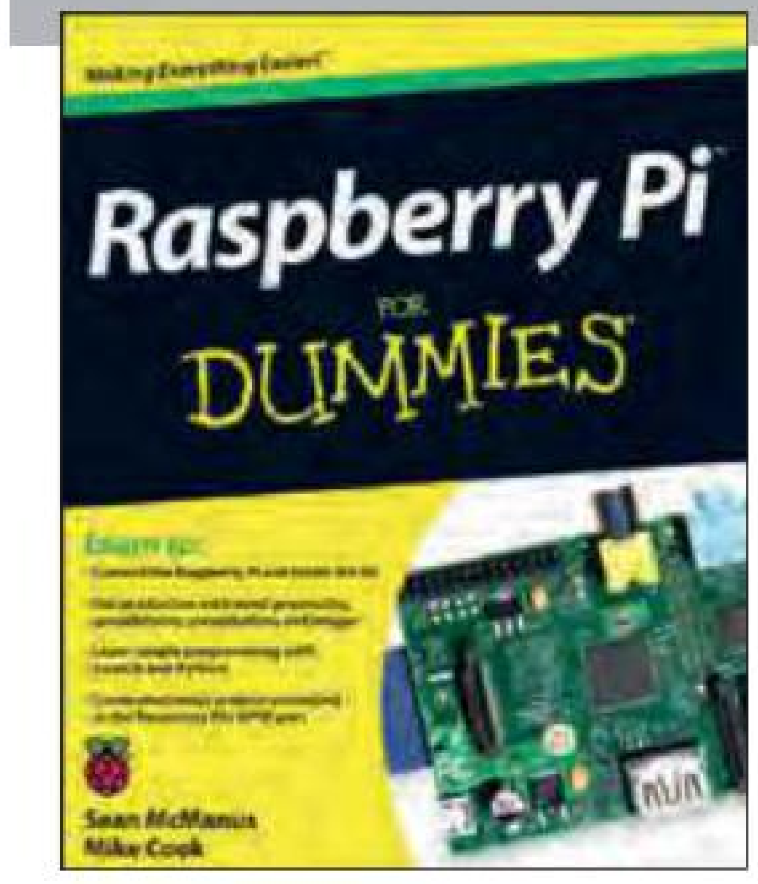

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Sean McManus and Mike Cook

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Mike & Richard Tooley

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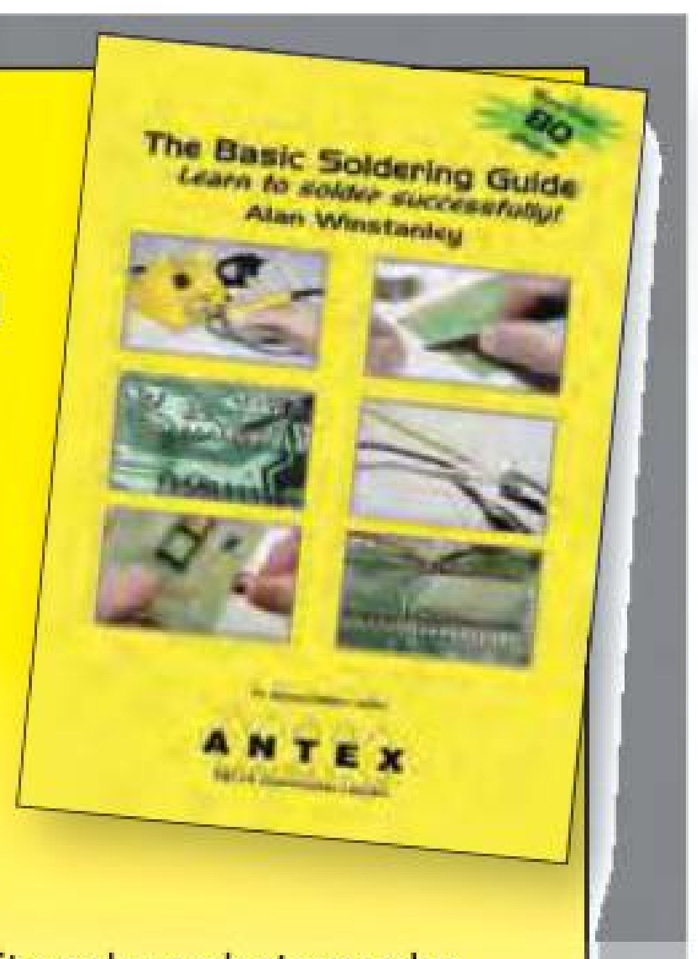

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Electronic Building Blocks

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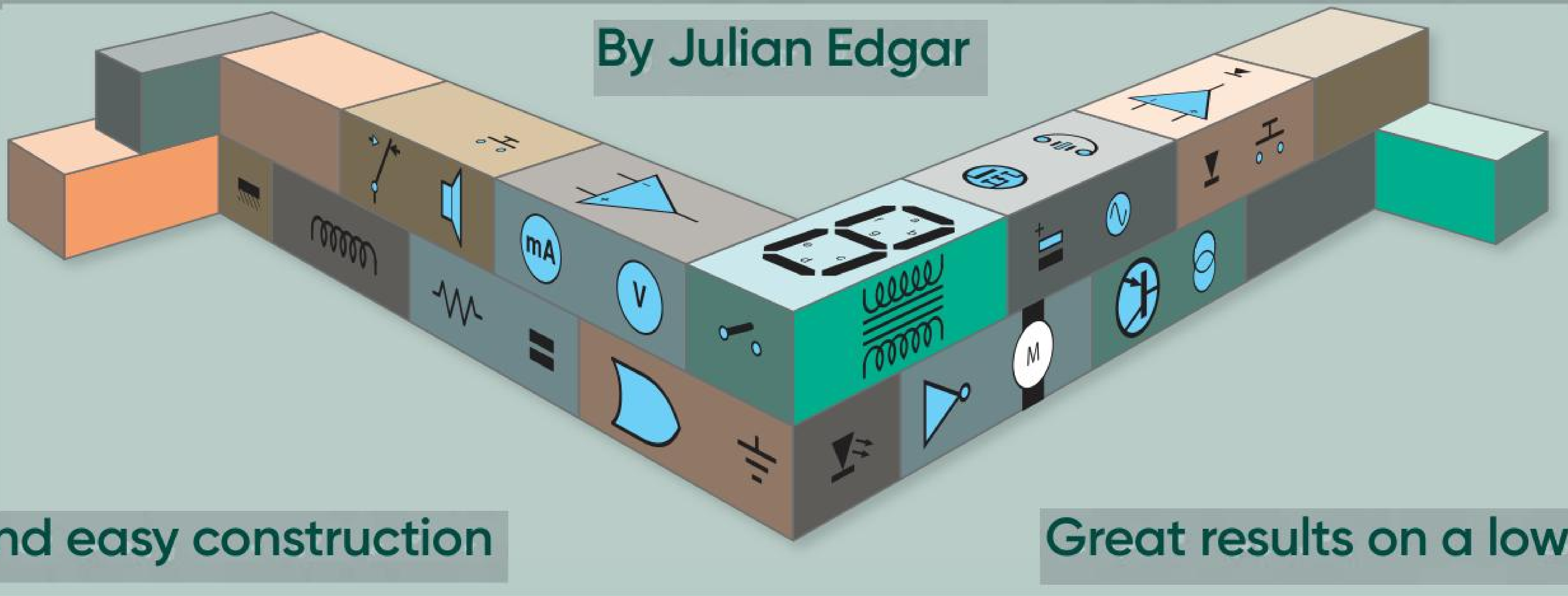


Quick and easy construction

Great results on a low budget

Hand-cranked LED torch

These days, wind-up torches are everywhere – and they're inexpensive, too. So why would you want to make the one shown here?

Well, here's some very good reasons. First, low-cost store-bought wind-up torches use cheap and nasty rechargeable batteries. A torch that has excellent performance straight after you bring it home from the shop (you know, 30 seconds of winding and it stays on for minutes) becomes less and less effective as time passes. In fact, I've had store-bought wind-up torches which, after a year, hold no charge at all – it's a wind-up torch that you need to keep winding all the time – which is a wind up!

In comparison, the design shown here uses a super-capacitor pack that should last for a very long time. I didn't want to wait a decade before we could run this story – but I can refer to capacitor-based wind-up torches I made 15 years ago that still work perfectly. This is a torch that should last for years and years… and years.

The hand-cranked LED torch uses a super-capacitor pack and a geared-up stepper motor as an alternator. Performance is very good, especially the length of time the LED will stay bright after you've stopped winding.

Second, most wind-up torches stay illuminated for quite a brief time – one minute, for example. In contrast, after winding, this design will stay bright for 10 or 15 minutes – and the LED will stay visible for something like seven or eight hours!

The torch is ideal for your bedroom, or to lend to a visitor so they can find the bathroom at night. It's not a super-bright searchlight, but it is great for moving around after lights out.

Design

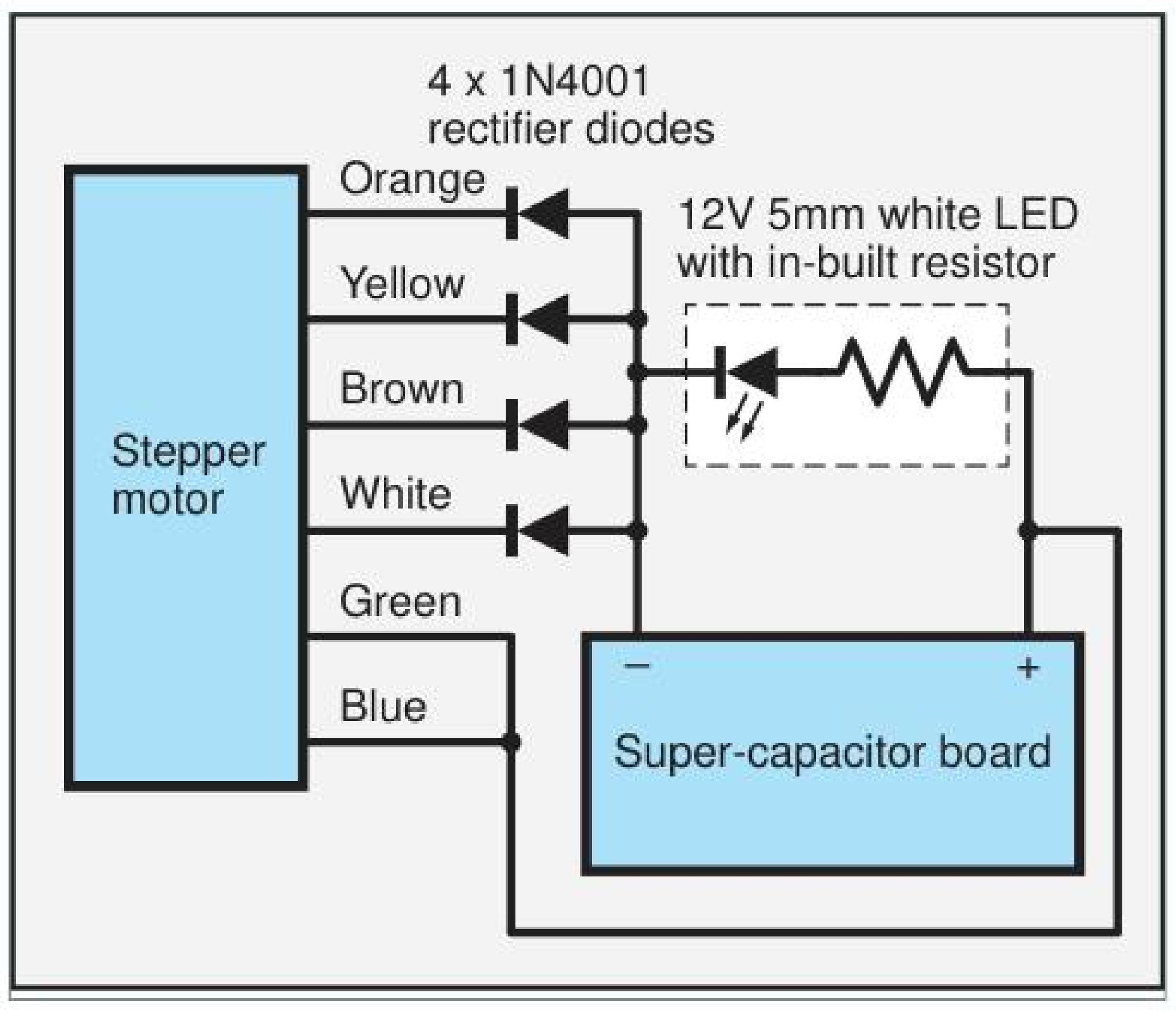
The starting point for the torch was the bicycle lighting system covered in the November 2018 issue of *EPE*. That design used a hub dynamo, a buck/boost converter and a super-capacitor pack. On the *EPE/PE Chatzone*, a reader wrote enthusiastically about the bike lighting system, but asked if it could be done without the bike? Serendipitously, at the same time as that post appeared, I was looking for off-the-shelf parts that could be used to make an LED wind-up torch. (I wanted to avoid the route taken in the past of simply testing a heap of salvaged stepper motors until a good one was found.) The outcome of those ideas can be seen in the mini project presented here.

To develop power, the torch uses a tiny stepper motor (one with doubled windings) that acts as an alternator. This small unit (mounting centres are just 31mm apart) comes complete with a gearbox. The one I chose costs just £1.99 including delivery – search on eBay using '20mm 12V Reducer Stepper Stepping Motor Full Metal Gear Reduction Ratio 36:1'. (For example, at the time of writing, eBay item 173585069531.) The motor's tiny gearbox uses metal gears, and the 36:1 step-up ratio means that when the input shaft is being turned twice a second, the internal stepper motor is rotating at over 4,000 RPM!

The project is ideal as a bedroom torch or similar. After a few minutes of winding, the LED will stay visible all night!

We connect a crank (handle and knob) to the shaft of the motor, allowing it to be easily turned. This is a little trickier than it sounds, because the shaft uses a D-shape cross-section and it is very small in diameter. The easiest way of connecting a handle is to use high-density polypropylene (the plastic that kitchen chopping boards are made from) to form the handle, then drill a 2.5mm hole at one end. The handle's crank then becomes a tight push-fit on the shaft, gripping it quite securely. At the other end of the crank, we use two parallel ball-bearing races to form a spinning knob, fixed with a bolt. Drill the hole for the bolt slightly undersize so that the threads cut into and grip the polypropylene. The bearings we used were

The stepper motor – that we use as an alternator – uses a 36:1 gearbox equipped with metal gears. Turning the torch handle a few times a second results in an alternator speed of over 4000 RPM.



Carefully follow these colour codes for the stepper motor wiring, and the orientation of the diodes. The selected LED uses a pre-wired resistor.

15mm OD and 5mm ID – any similar size will work fine.

Inside, the outputs of the stepper motor alternator are rectified using diodes, with the DC output fed to both a white LED and the pre-built super-capacitor module. The capacitor pack is available on eBay and is usually called, '16V1F/2F Farad Capacitor Module 2.7V 10F Supercapacitor With Protection Board' (for example, at the time of writing, eBay item 232879025831). It will cost you about £5 delivered. The board uses six 2.7V, 10F capacitors, plus some protection circuitry (mounted on the rear of the board).

Despite trialling different circuit approaches that used a buck/boost converter and an LED driver board, best results came from keeping it simple. The design uses a white LED sold for use on 12V, and so is equipped with an appropriate dropping resistor – see Banggood ID item 82464 (10 off, prewired 5mm bright white for £1.57 – delivered!). The LED was wired in parallel with the super-capacitor board. In the final design, a buck/boost module was not used – interestingly, when trialled, it gave no benefit.

An on/off switch was not fitted, and the torch was housed in a strong utility plastic box of 83 x 58 x 34mm outside dimensions.

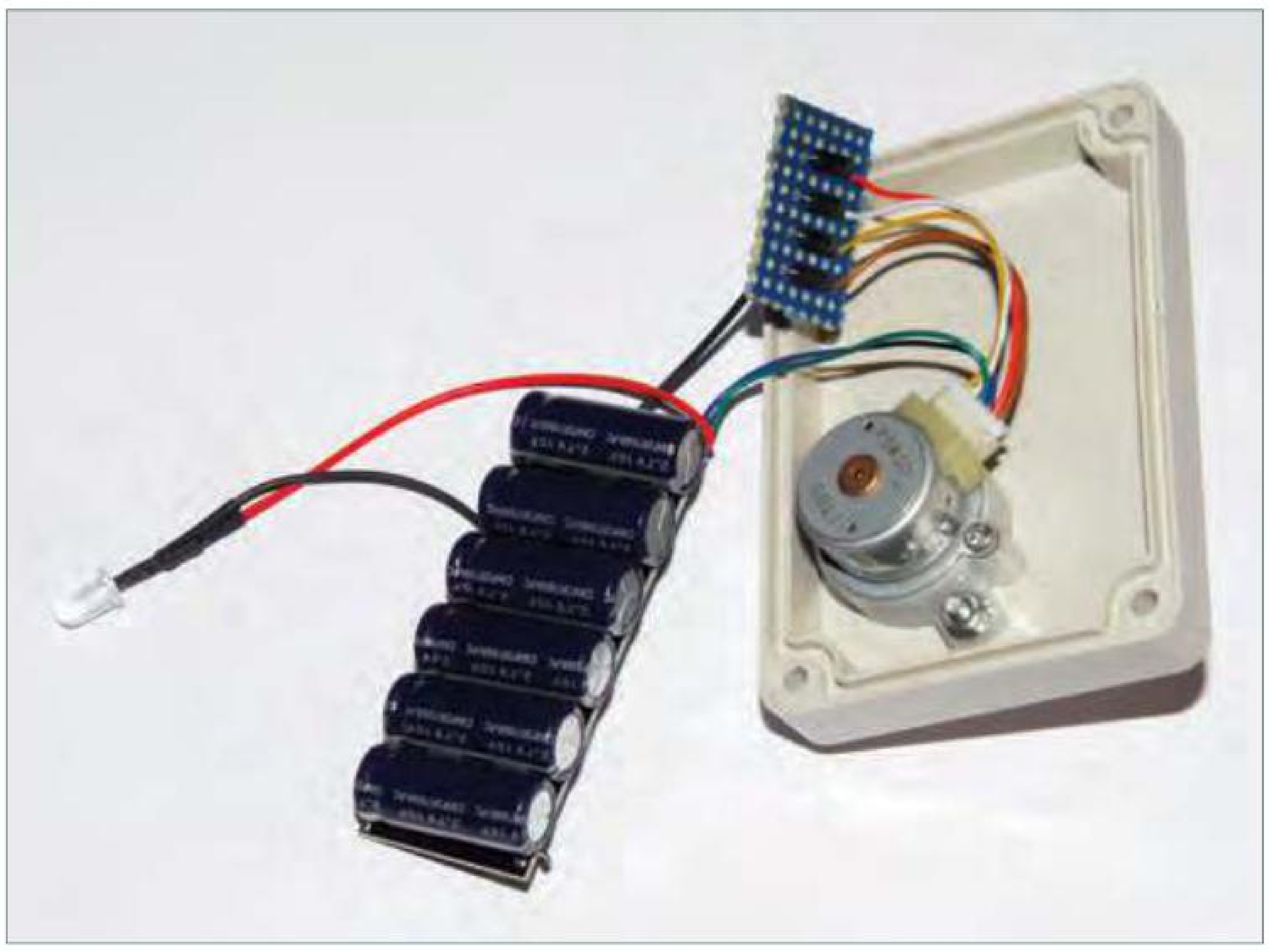
Building the torch

Mount the stepper motor in the lid of the box, and make and fit the handle. Polypropylene can be cut with normal woodworking tools – and you did need a new kitchen chopping board, didn't you…?

The stepper motor has six connections that can be subdivided as follows:

Winding 1 orange, yellow and green
Winding 2 brown, white and blue

For the rectifier, I used cheap-as-chips (actually, cheaper) 1N4001 diodes. Connect the orange, yellow, brown and white wires to individual diodes – cathode (band on diode body) nearest the stepper. The other ends (anodes) of the diodes are connected together – this forms the negative output. You can mount the diodes on a small piece of pre-punched board, or wire them in free space, covering them in heat-shrink. Connect together the green and blue wires from the stepper – this forms the positive output. Now turn the input shaft and use your multimeter to check you have a DC voltage across the output.



The stepper motor / alternator AC output is rectified with the diodes and then fed to the pre-built super-capacitor board and, via an in-built dropping resistor, to the LED. This simple approach works really well with the specified components.

Drill a hole in the case for the LED, and wire the LED and capacitor pack into place. Wrap the capacitor board in insulating tape (and also do the same for the diode board, if you've used one) and fit all the parts in the box. You might need to juggle the components to get them in – the capacitor pack is a tight fit. A small piece of foam rubber inserted into the box will help stop any components rattling.

In use

It's simple – you wind the handle, and the LED quickly lights up. If you wind the handle for a minute or two, the capacitor pack will be charged to about 7.5V. With the capacitor pack driving the LED, after around five minutes the voltage will have dropped to about 4.3V, after 10 minutes to 3.4V, and after 30 minutes to 2.7V. Such is the quality of modern LEDs, the light will still be quite useable in a dark area for all this time.

And how long does the LED stay visible – that is, bright enough that you can find the torch in the dark? Depending on the LED, something like seven or eight hours!

One reason for using the 12V LED (and its appropriate dropping resistor), and the 16V capacitor pack, is that you cannot over-wind the torch – the maximum available voltage does not exceed 12V.

You could, of course, fit an on/off switch, but after I stop winding the torch, I find the ever-so-slow dulling of the LED fascinating. (The lack of switch also reminds me that there are no batteries going flat.)

If you wind the torch nightly, every six months or so you might want to pull the gearbox apart and apply some very thin oil – this sort of oil is sold for use in sewing machines. On the other hand, at just £2 each, you could also buy some spare stepper motors! Swapping them should take less than five minutes – the wiring just plugs in.

So there we have it, a high-performance, easy-to-build LED torch that never needs batteries and is always ready for action.

Next month

In May 2019's E*lectronic Building Blocks* we'll have some fun looking at a very useful multi-purpose variable duty cycle and frequency driver – a multi-pulser.

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Next Month – in the May issue

USB Port Protector

Using a laptop to power a 5V project is very convenient – but make a small slip while plugging something into a breadboard and then...oops! This simple, economic device will swat the zaps!

2x 12V Battery Balancer

Two 12V batteries can be much cheaper than a 24V one, but you need to be careful wiring batteries in series as their state of charge may differ. This compact device keeps them balanced so that they last a long time.

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Teach-In 2019 – Part 6

In *Part 6* of *Teach-In 2019* we will introduce voltage multipliers and our *Practical Project* will be a simple low-current 9V-to-15V supply converter.

Backing Baxandall – Part 2

In *Part 2* of this *Audio Out* project we'll show you how to build a four-capacitor Baxandall tone control.

PLUS!

All your favourite regular columns from *Make it with Micromite* and *Circuit Surgery* to *Electronic Building Blocks*, *PIC n' Mix*, *Techo Talk* and *Net Work*.

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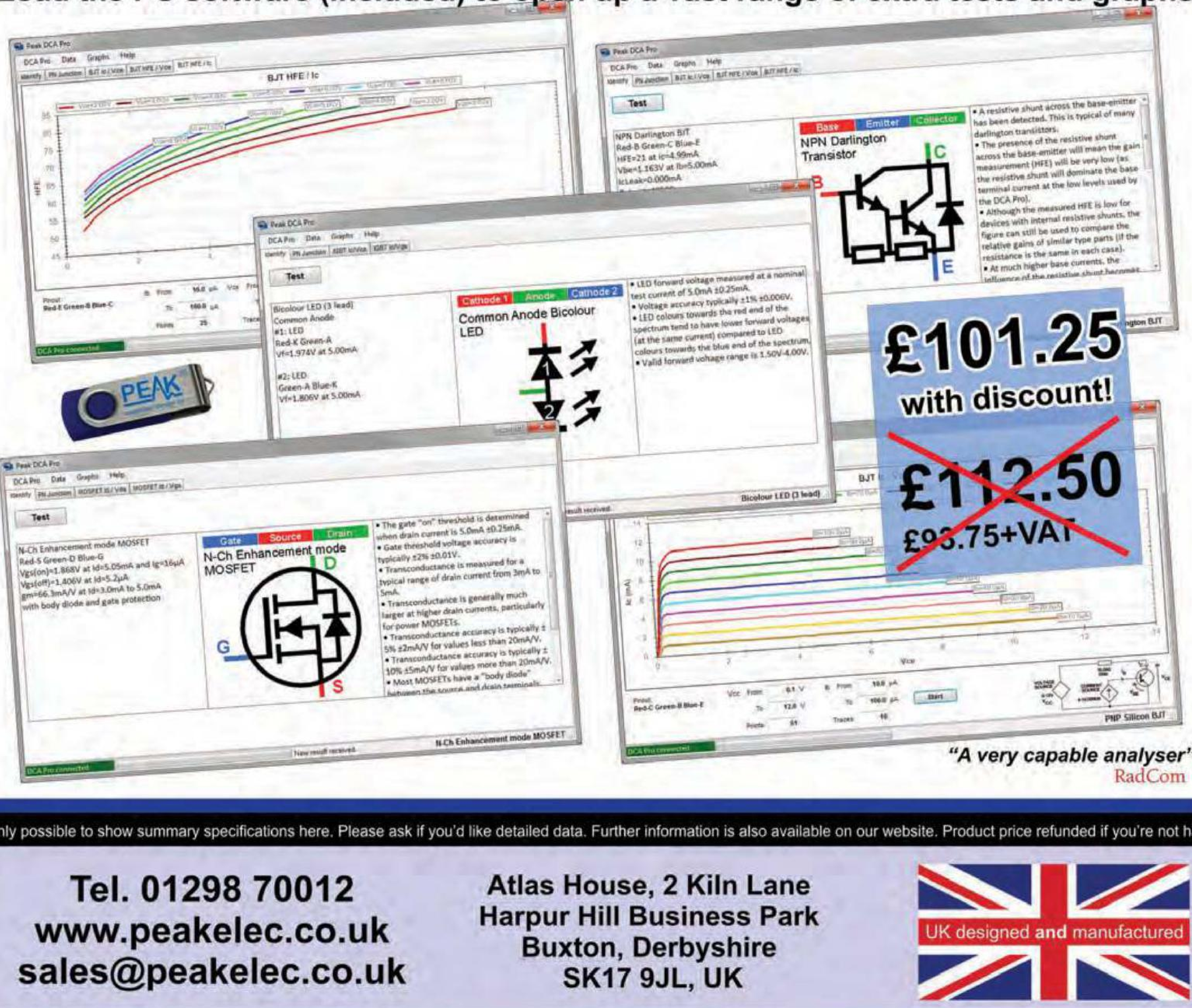
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Bicolour LED (3 lead)
Common Anode
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Red-K Green-A
Vf=1.974V at 5.00mA

#2: LED
Green-A Blue-K
Vf=1.806V at 5.00mA

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Bicolour LED (3 lead)

N-Ch Enhancement mode MOSFET
Red-S Green-D Blue-G
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